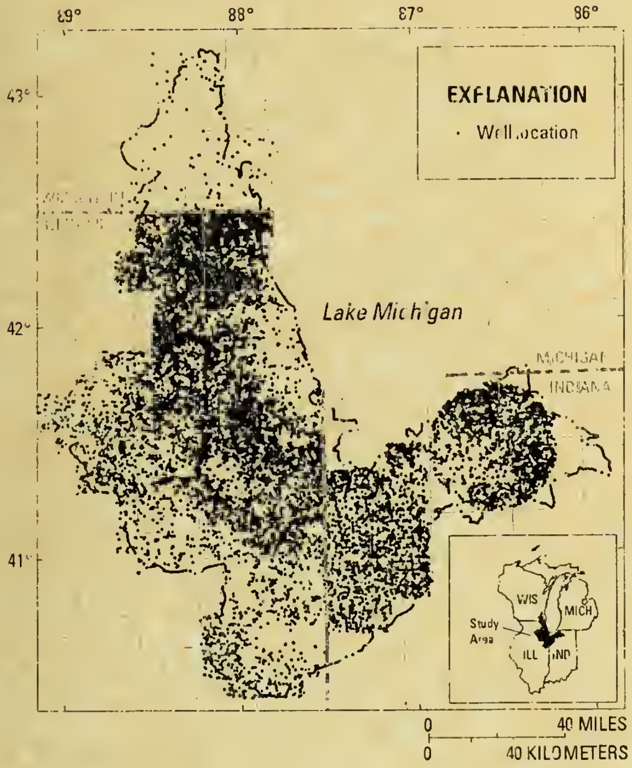
OFS 2001-1

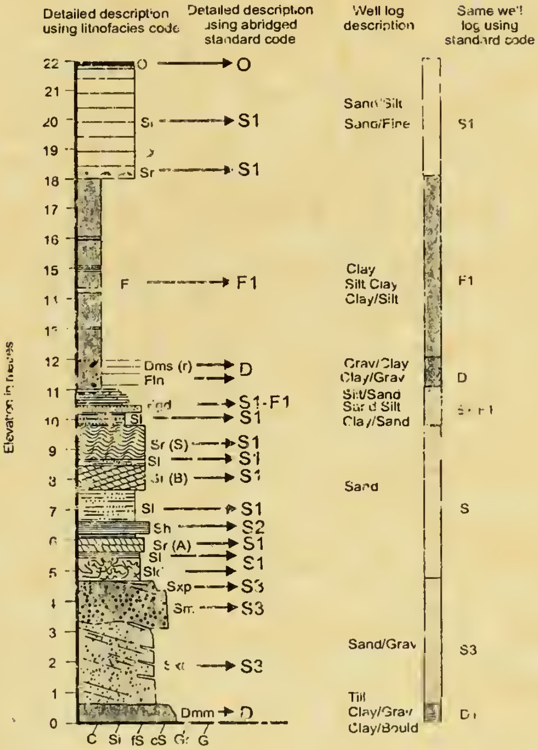
Geological Models for Groundwater Flow Modeling

Workshop Extended Abstracts

Convenors:

Richard C. Berg
L. Harvey Thorleifson





April 22, 2001
35th Annual Meeting
North-Central Section
Geological Society of America

Open File Series 2001-1

George H. Ryan, Governor

Department of Natural Resources
ILLINOIS STATE GEOLOGICAL SURVEY
William W. Shilts, Chief

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Introduction - Developing large, diverse data sets, and constructing three-dimensional geologic and groundwater models

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This workshop is designed for those concerned with the development and management of the large, diverse databases that are required for construction of three-dimensional (3D) geologic models and for modeling groundwater flow. Our emphasis is on the data and types of 3-D models needed to portray Quaternary and pre-Quaternary unconsolidated deposits that host potable groundwater and that are the context of most waste-disposal and other environmental issues.

The first key theme focuses on the challenges presented by integrating of large data sets, including both data of variable quality such as logs from water wells, with the crucial high quality data such as from engineering and test boring logs and from geophysics. Presenters will address several of these challenges such as:

- Selecting key stratigraphic boring logs ("golden spikes") and integrating them with lower quality data
- "Screening" lower-quality data and selecting the "best" information
- Determining data adequacy (scale dependent)
- Developing a viable and user-friendly database

The second key theme concentrates on the use of data to construct 3-D models of the geology. The model may consist of multiple cross sections, fence diagrams, block diagrams, individual isopachous and structure contour (elevation) maps, stack-unit maps, etc. General areas to be addressed by the presenters include:

- Evaluating and using data of variable quality and quantity for constructing 3-D models
- Determining what types of 3-D models "best" portray the geology
- Determining which models are most appropriate for development of derivative maps, such as those needed for groundwater investigations
- Developing internally consistent 3-D models that avoid having lower horizons occurring above upper horizons

The final theme focuses on one important end user of 3-D maps and supporting databases - the groundwater professional - who is charged with modeling the flow and direction of groundwater and whose model results directly will be used for decisions including mitigation/clean-up, water-resource allocations, and other planning and land-use issues. General areas that presenters will address include:

- Evaluating specific end-user needs of hydrologists/hydrogeologists
- Determining specific data requirements of hydrologists/hydrogeologists
- Getting geologists and hydrologists/hydrogeologists interacting to modify and refine 3-D geologic models
- Explaining how hydrologists/hydrogeologists deal with very complex settings

The workshop offers the opportunity for those involved to share their ideas about acquiring, evaluating, and compiling geologic data, constructing 3-D maps, and using 3-D maps and data for groundwater modeling. At some institutions, separate specialists conduct the tasks of compiling geologic data, constructing 3-D maps, and modeling groundwater. However, more commonly, a team of geologists and hydrogeologists perform all three tasks or one individual may perform at least two and perhaps all three tasks. It has become apparent to the workshop convenors that, regardless of who performs the tasks, the methodologies for dealing with large data sets and making 3-D geologic and groundwater models have some differences and some similarities depending on who and where the work is being done. Therefore, the primary goal of the workshop is to encourage interaction between participants from the United States and Canada who have dealt with these challenges.

Hydrogeologic inventory of the upper Illinois River Basin – Creating a large data base from well construction records

Arnold, T.L., M.J. Friedel, and K.L. Warner, U.S. Geological Survey, Urbana, IL 61801

A large data base consisting of 40,679 well locations and 196,687 lithologic records was created from Illinois, Indiana, and Wisconsin well construction records for wells drilled during the period 1980-1997. The purpose of the database is to provide information for mapping the surface, thickness, transmissivity and hydraulic conductivity of the Quaternary, Silurian/Devonian, and Cambrian/Ordovician age aquifers in the upper Illinois River Basin (UIRB). These digital maps and information will be used for the UIRB study of the National Water-Quality Assessment Program, U.S. Geological Survey (USGS), to facilitate county- or basin-wide three-dimensional (3-D) ground-water flow and transport modeling. A geographic information system (GIS) was used to create and manage the database. Over 50 computer programs were written and utilized to compile and summarize data from various sources.

The challenges of creating this large hydrogeologic database were in assembling the differently formatted data from diverse sources and in summarizing the data for application to 3-D ground-water flow and transport modeling. The first challenge was dealing with differently formatted data. The data consisted of location, lithologic, construction, and aquifer-test information for 40,736 wells (203,286 lithologic records) and were obtained from Illinois State Geological Survey (ISGS), Indiana Department of Natural Resources (IDNR), and Wisconsin Department of Natural Resources (WDNR). Only wells with complete locational information and lithologic records were included in the data base (fig. 1). There were 34,373 wells from Illinois, 6,175 wells from Indiana, and 131 wells from Wisconsin. The amount of data from WDNR was limited because, at the time the data was obtained (1997), paper well records only were recently compiled into a digital database. A total of 196,687 complete lithologic records were available from the three agencies. Different data base layouts and formats are used by the three agencies. Major differences in the data were order of presentation, units of measurement, and types of recorded information. Because of these differences, some data had to be reformatted, calculated from existing data, or re-ordered so that it could be uniformly compiled into one database. The large size of this data set made it difficult to rearrange data columns and to process because each processing step took multiple days of run-time on the computer. In addition, each agency had a different method for retrieving data from their databases. ISGS required township and range locations, IDNR required spatial polygons defining the area of interest, WDNR required county names. Because of the different data-retrieval requirements, the outer edges of the UIRB were not adequately covered by wells (fig. 1). The few wells available from Wisconsin also provided relatively poor coverage of the Wisconsin portion of the basin.

The lithologic data from each agency were compiled into related data files and three digital maps were made from the locational information. Different well-numbering systems were used by each agency to uniquely identify the wells in their databases. To create a unified database, unique USGS-format well-identification numbers were assigned to each well. The information associated with each digital map was placed in the same format and map projection and the maps were joined digitally. After reformatting and joining the related files, the well information in the data base included: IDNR well identification (ID) number, ISGS American Petroleum Institute (API) well ID number, WDNR well ID number, construction date, longitude, latitude, Universal Transverse Mercator (UTM) zone 16 x-coordinate, UTM zone 16 y-coordinate, Lambert x-coordinate, Lambert y-coordinate, State Plane x-coordinate, State Plane y-coordinate, township, township direction, range, range direction, section, topographic quadrangle name, FIPS state and county code, State name, County name, hydrologic unit code, land-surface altitude, well depth, water level, discharge, pump time, drawdown, casing length, casing top, casing bottom, casing diameter, screen length, screen top, screen bottom, screen diameter, lithologic records from well construction (depth to top and bottom of lithology and lithologic description).

The second challenge was summarizing the data for mapping and use in hydrogeologic models. For each well location there are many lithologic records that describe the stratigraphy that the well penetrates. To summarize the information, lithologic ages were estimated and depths to the top of the Silurian/Devonian, and Cambrian/Ordovician aquifers were identified. The data recorded for each well provided different information about the various aquifers because not all wells penetrated each aquifer (table 1).

The lithologic descriptions were inconsistent among wells from the three agencies and also within a particular agency. Various word combinations were pattern-matched to create a common descriptor for each lithology. Once consistent lithologic descriptors were established, each descriptor was attributed with an aquifer code that described the material as unconsolidated or bedrock. A quality check was performed to ensure that aquifer codes were in a logical sequence. For example, ensure that no unconsolidated material is listed in the related lithologic data file as being present underneath bedrock material. Errors in the sequence of lithologic records, such as the top of an underlying lithology listed as above the bottom of the overlying lithology, were identified and corrected manually. After examining hundreds of lithologies, patterns in descriptions became apparent and these patterns were used to help identify correct sequences.

To facilitate correcting the sequence of lithologies and later identifying the lithologic age, a stratigraphic table was compiled based on the “Handbook of Illinois Stratigraphy” (Willman and others, 1975), “Compendium of Rock-Unit Stratigraphy in Indiana” (Shaver and others, 1970), “Bedrock Geologic Map of Indiana” (Gray and others, 1987), “GEOLEX Data base—National Geologic Map Data Base” (U.S. Geologic Survey, 1999), and “Hydrogeologic Atlas of Aquifers in Indiana” (Fenelon and others, 1994). The stratigraphic table did not include Wisconsin lithologic units because the formation and age of lithologies for wells in Wisconsin were identified previously by WDNR. The compiled stratigraphic table included group/series and formation name, age, approximate thickness, description of color and texture, and spatial extent.

Ages associated with a lithology were identified after the stratigraphic table was compiled. Because a goal was to map the top of the Silurian/Devonian, and Cambrian/Ordovician aquifers and thickness of the Quaternary and Silurian/Devonian aquifers, emphasis was placed on identifying the lithology of age-specific aquifers. Formations were identified, when possible. If formations could not be identified, the lithology was attributed with ‘unidentified’ formation. All lithologies with an aquifer code of ‘unconsolidated’ were attributed as ‘Quaternary’ age and ‘undifferentiated’ formation. The more difficult task was determining which bedrock lithologies were Silurian/Devonian and which were Cambrian/Ordovician. In parts of the UIRB, Mississippian/Pennsylvanian bedrock also is present. To aid in identifying bedrock lithologies of a specific age, the uppermost bedrock was needed to provide a starting point.

Uppermost bedrock age and formations previously have been mapped in Illinois (Willman and others, 1975), Indiana (Gray and others, 1987), and Wisconsin (Wisconsin Geological and Natural History Survey, 1981). A new map was compiled from these State maps to show uppermost bedrock age and formation in the UIRB (Arnold and others, 1999; fig. 4). This map provided a gross definition of the age of the uppermost bedrock. Wisconsin lithologic records contained formation and age recorded by the WDNR. Therefore, these Wisconsin lithologic records were not examined during the process of identifying formations and ages for the database. Every record in the lithologic data file for each well was examined and the first entry of bedrock material was identified as the top of the bedrock surface and attributed with the age and formation of the uppermost bedrock. For the wells that ended in bedrock material, the lithologies of each well were attributed interactively with formation and age. In most cases, identification of ages was straightforward and formation names easily followed the compiled stratigraphic table. However, some lithologic records did not agree with the map of uppermost bedrock (probably because of map scale). If a lithology could not be associated with the stratigraphic table and map of uppermost bedrock, the formation was attributed as 'undifferentiated' or 'unknown' and the age was estimated by the lithologies above and below the unidentified one. Marker beds, such as the Maquoketa Shale, indicated where the age of the bedrock material changed. However, these marker beds are not always present. When the marker beds couldn't be identified from the lithologic records, age was recorded as 'unknown' and formation was recorded as 'unidentified'.

To calculate the hydraulic properties (transmissivity and hydraulic conductivity), several pieces of information were required: duration of aquifer test, well discharge, drawdown during pumping, well diameter, screen length, and aquifer thickness. The thickness of permeable material in each aquifer was calculated to estimate aquifer thickness. Wells without the required information were not used in transmissivity and hydraulic conductivity calculations. Some of the wells had incorrect or missing well-construction information. In order to include as many wells as possible with sufficient information for calculating the hydraulic properties, the well construction information was added or corrected, if possible, based on available information about the well.

After all information was summarized, geostatistical software was used to evaluate and statistically model spatial structure of the Silurian/Devonian and Cambrian/Ordovician aquifer surfaces and the thickness of the Quaternary and Silurian/Devonian aquifers. Results of the geostatistical modeling provided statistically unbiased estimates of depth to the top of the Silurian/Devonian and top of the Cambrian/Ordovician aquifers; and thickness of the Quaternary and Silurian/Devonian aquifers. The software also was used to make preliminary maps of the transmissivity and hydraulic conductivity of each aquifer. Prediction standard error maps were utilized to identify regions characterized by differing amounts of uncertainty.

Developing a hydrogeologic database of this size is a long process that requires careful planning. Most important in data base development is that the interpretation of lithologies and assumptions are made under the supervision of an experienced geologist. Well construction records are neither the most consistent nor accurate source of geologic information but they are the most geographically widespread snapshots of underlying geology. The advantage of using well construction information over drilling additional wells is the lower cost. The only cost of using existing data is that of the data itself and personnel time for processing the data into a comprehensive geologic database. Once the database is made, it can be used for 3-D modeling in a variety of applications.

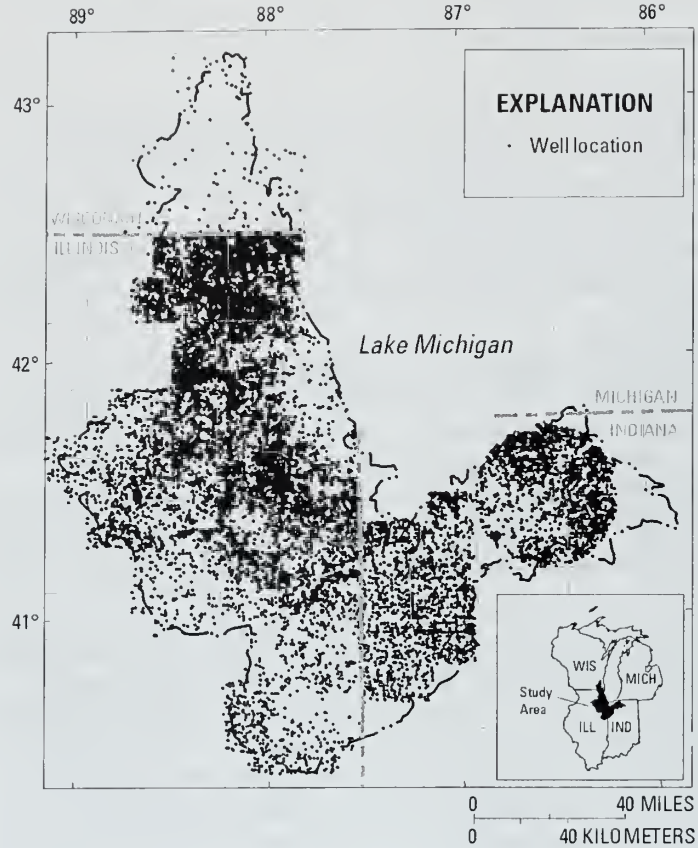

Figure 1. Location of wells included in the hydrogeologic database of the upper Illinois River Basin.

Table 1. Information provided by wells in the hydrogeologic data base.

Information Provided	Number of Wells	Percent of Wells in Data Base
Depth to top of Silurian/Devonian aquifer	17,000	42%
Depth to top of Cambrian/Ordovician aquifer	6,555	16%
Thickness of Quaternary aquifer	22,370	55%
Thickness of Silurian/Devonian aquifer	1,836	5%
Transmissivity and hydraulic conductivity	10,248	25%

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Developing the database for 3-D modeling: acquiring, assembling, verifying, assessing, interpreting, and integrating source data

Michael L. Barnhardt, Ardith K. Hansel, and Andrew J. Stumpf, Illinois State Geological Survey, 615 E. Peabody Dr., Champaign, IL 61820

Lake County, Illinois contains some of the most rapidly growing communities in the state, many of which rely heavily upon groundwater resources. Accurate maps of the aquifers within the thick Quaternary sediments (up to 400 feet thick) are needed by agencies and local governments for infrastructure planning, resource development, land use planning, and environmental protection. The sources of data necessary to produce these maps vary in their point of origin, availability, content, and many other factors.

Modeling subsurface stratigraphy requires a considerable effort to develop the database. High quality geological data from boreholes with inaccurate spatial reference is as useless as poor-quality data from accurately located boreholes. Also, the variation in complexity of the subsurface stratigraphy influences data requirements. The spatial density and quality of data available for use in modeling are variable and additional drilling is often required in specific locations to supplement existing data.

During the past year our team has invested more than 4.5 work years acquiring, verifying, and interpreting the drilling records and/or logging the sediments from about 7,000 borings primarily in the Antioch Quadrangle as part of a Pilot Study for the Central Great Lake Geologic Mapping Coalition. These records include water wells and foundation borings for bridges, highways, and utility and telecommunication towers. We will be examining the drilling and other records from more than 200 projects conducted by a private engineering consulting firm. These projects were located in very urbanized and restricted access areas, so they will be a valuable source of quality geotechnical data. More than 200 sets of sediment samples, collected during the drilling of various water wells over the years and stored in the State Geological Survey's sample library, have been examined and described. We are also drilling in areas where data are lacking and in areas where our borehole descriptions can be used to interpret the driller's logs from surrounding wells that have been spatially verified. A program of gamma logging of new water wells in the area is providing valuable information on subsurface stratigraphy and will be integrated into our shallow seismic geophysical research.

We have verified more than 3,000 boreholes using plat books, tax parcel and address matching, and field verification techniques. Now these spatially-located records must be interpreted and sorted by quality of information and location and their descriptive driller's records translated into more standardized data formats. This process will further reduce the number of viable records because some of the verified data will not have information useful for modeling. One product of this evaluation process will be a method that provides a more consistent assessment and characterization of geological records in the area. We hope this methodology for organizing data can be transferred to other areas.

All these different types of records must be integrated in a single database before any modeling can begin. But, once initiated, the modeling should provide interesting and useful insights. Our mapping team will then begin to test this model using additional drilling and geophysical fieldwork. Our clients are expecting more than a standard 3-D visualization. It will be our challenge to integrate these records and the expertise of mappers, stratigraphers, groundwater geologists, sedimentologists, geophysicists, and GIS/database specialists to produce products that not only detail the geology but permit an in-depth analysis which will include an assessment of our confidence in the data and the rationale supporting our interpretations.

Geological model for groundwater flow studies, greater Ottawa, Canada

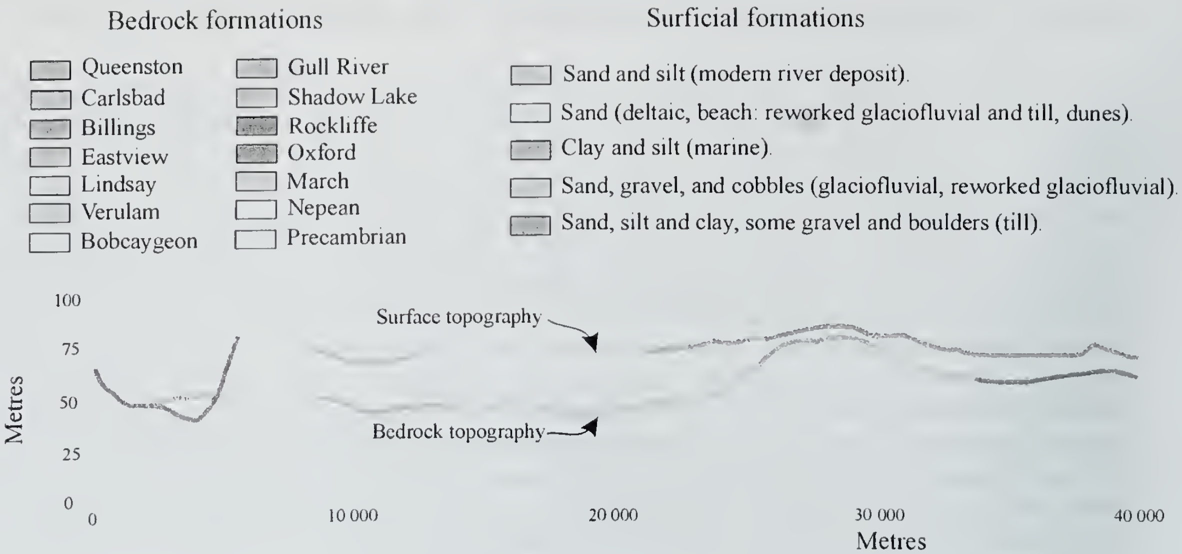
Bélanger, J. Robert, Geological Survey of Canada, 601 Booth Street, Ottawa, Canada, K1A 0E8

Urban and suburban development is spreading at a fast pace in Canada's National Capital area. Local and regional governments are using existing geological maps and documents for regional planning purposes, and are requesting more geoscience information that they consider essential for environmental protection, identification of natural hazards and development of urban infrastructure. As a response to users' need, the Geological Survey of Canada initiated an Urban Geology project, to provide a 3-D geological model to be used in environmental studies, hydrogeology and regional planning. The major challenge encountered in the production of the model was to combine data coming from different sources and formats, produced for different purposes and having different levels of reliability.

The 3-D geological model was built in four phases: compilation and standardization of source information, production of derived and integrated maps, production of stratigraphic sections, and integration of stratigraphic sections into a 3-D model. Source information came from geological maps (surficial and bedrock), digital topography (DEM), and borehole information (Subsurface Database). The surficial and bedrock maps were compiled from existing maps at different scales and from different authors and legends, but this type of compilation is more a conciliation challenge than a technical problem when using modern GIS software. A greater challenge, however, was the integration of borehole information coming from different sources, using different terminology and having differing reliability. The Subsurface Database contains stratigraphic information from 2370 engineering boreholes, 23192 water well logs and 1610 shallow seismic profiles. The original data were first validated to eliminate obvious errors. Then the terminology describing soil horizons was standardized, based on the texture of material, to permit correlation between boreholes; the original information was kept to permit back reference when further information is necessary for geological interpretation.

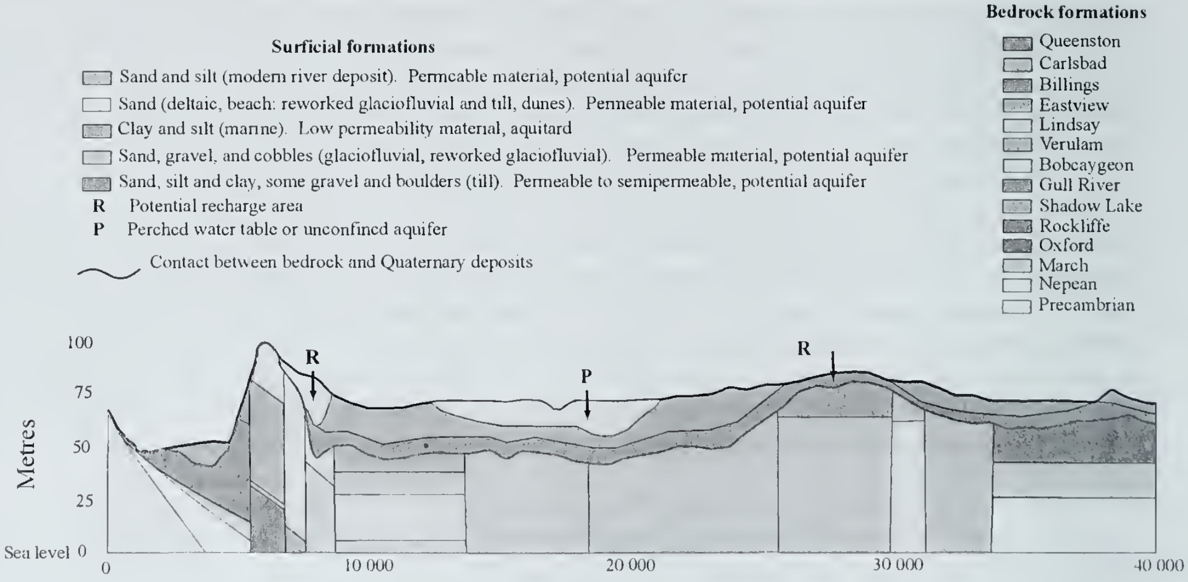
The second step in building the 3-D model is the production of derived maps to provide the third dimension of the 2-D polygonal maps. A drift thickness map was produced by interpolating a continuous layer from control points derived from the surficial geology map and the subsurface database. The surficial geology map provided control points where no data are available from the subsurface database, by giving minimal values in drift covered areas, and maximum thickness in areas mapped as bedrock outcrops. The second derived document is the bedrock topography map, which is obtained by subtracting the drift thickness from the surface topography map, provided by the digital elevation model.

The stratigraphic sections were produced using a computer-assisted approach. A (module) was programmed in ESRI AML (Arc/Info) to provide a "skeleton" stratigraphic section, showing the surface topography, bedrock topography and nature of surficial materials and bedrock along the two topographic lines (Figure 1). These lines are derived from the surficial and bedrock geology maps, the DEM, and the bedrock topography map. Stratigraphy is then drawn manually within the skeleton section based on borehole information surrounding the stratigraphic section (Figure 2). The Subsurface Database is queried online (Figure 3), but very little automation can be achieved in building the stratigraphic section, due to the unreliability of geological descriptions provided by the water well records. Building a 3-D model by integrating the 2-D stratigraphic sections is presently under development.



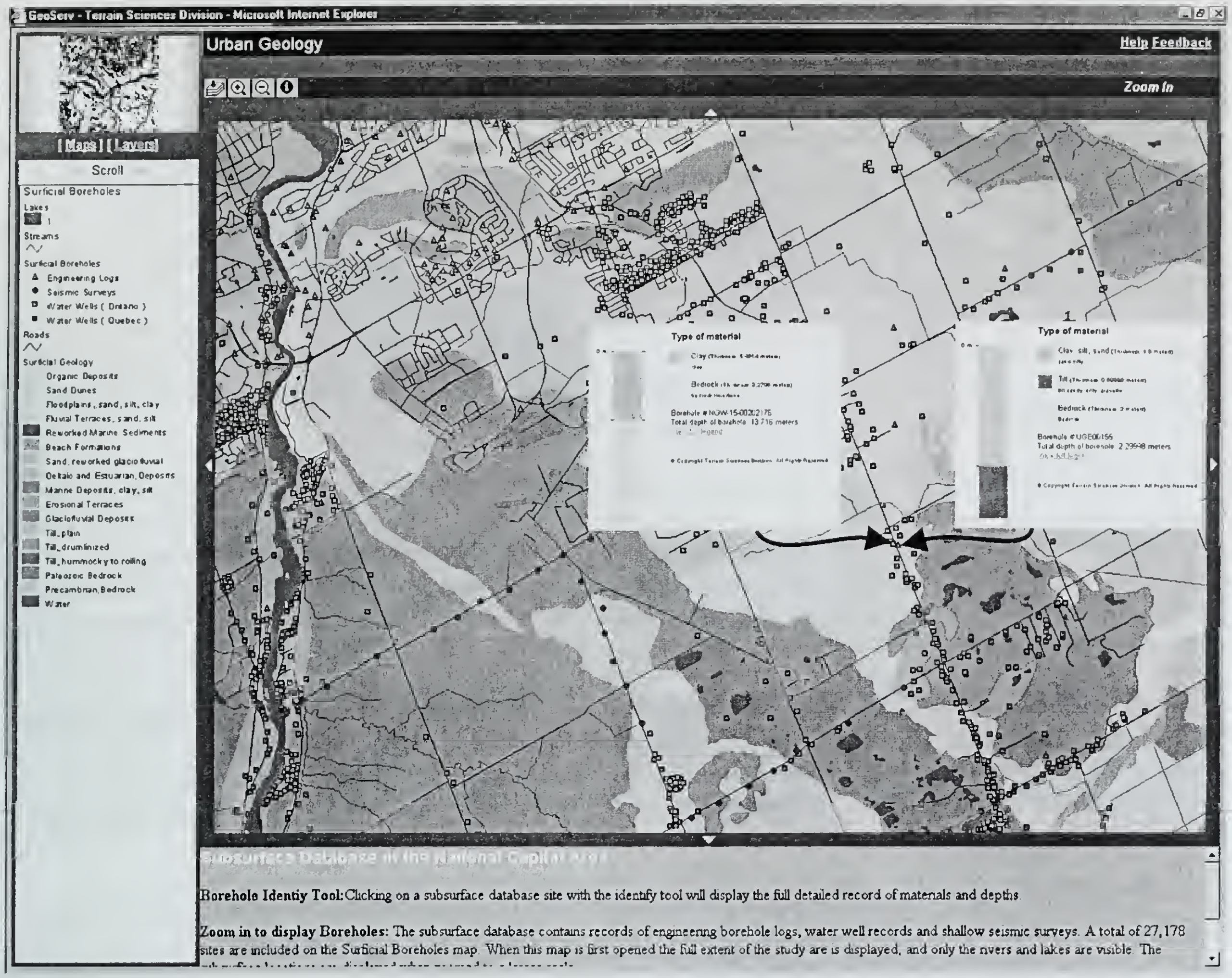
Skeleton Stratigraphic Section

Figure 1



Stratigraphic Section
Derived from boreholes and skeleton section

Figure 2



Borehole # NOW-15-00202176
Total depth of borehole 13.716 meters

Borehole # UGE00156
Total depth of borehole 2.29998 meters

Subsurface Database in the National Capital Area

Borehole Identiy Tool: Clicking on a subsurface database site with the identify tool will display the full detailed record of materials and depths.

Zoom in to display Boreholes: The subsurface database contains records of engineering borehole logs, water well records and shallow seismic surveys. A total of 27,178 sites are included on the Surficial Boreholes map. When this map is first opened the full extent of the study are is displayed, and only the rivers and lakes are visible. The

Online Query of Subsurface Database
Figure 3

Regional groundwater mapping and model

Boyd, Dwight[1], Steve Holysh[2], and Jeff Pitcher[1]

[1]Grand River Conservation Authority, Canada; [2]Regional Municipality of Halton, Canada

The Grand River forms one of the largest drainage basins in the southwestern portion of the Province of Ontario. The drainage area of the Grand River is approximately 6800 square kilometres, representing 10 percent of the direct drainage to Lake Erie. Agricultural and rural land use predominate, with urban land uses concentrated in the central portion of the watershed. Most of the basins' 800,000 residents reside within this central portion. It is estimated that 82% of the watershed's population are reliant on groundwater for their drinking water supply.

The Grand River Conservation Authority began updating their overall watershed management plan in 1996. This update is ongoing. A key objective of the plan is to develop a good technical understanding of the groundwater system throughout the watershed. Of particular interest are the linkages between the groundwater and surface water systems. Better understanding of these linkages allows for more effective resource management and better incorporation of groundwater issues and concerns into the planning process.

To help provide a technical understanding of the groundwater system, a systematic approach was taken in the assembling of geology, groundwater, topographic, and biological information. The deliverables of this effort will include regional scale groundwater mapping and a regional scale MODFLOW groundwater model. These tools will be used to assist with decision-making related to groundwater management.

To date, the regional scale groundwater mapping has been completed along with a detailed technical report describing the mapping. Furthermore, an uncalibrated regional scale MODFLOW model has been constructed using 200-metre cells across the entire watershed.

As was previously mentioned, a systematic process was followed to assemble the necessary background information for the project.

The first step was to compile and review all available geologic information. Geology significantly affects the underlying physics of a watershed and will impose a dominant control on the system. Ultimately, a seamless digital coverage representing the quaternary geology of the watershed was constructed. This work was done with the co-operation and assistance of the Ontario Geological Survey.

The next step in the process was to obtain and update water well information for the watershed. This information was obtained from the Ontario Ministry of the Environment. The Conservation Authority worked closely with the Ministry to update the existing data and to structure the water well information into an MS-Access database.

As the water well information was being updated, the Conservation Authority, in co-operation with the Ontario Ministry of Natural Resources, created a hydrologically conditioned Digital Elevation model for the watershed. This model was based predominantly on elevation data contained within 1:10,000-scale Ontario base mapping.

Once the majority of the background work had been completed, a two-member team including a hydrogeologist and GIS expert was assigned to produce the regional scale groundwater mapping and the accompanying technical report.

A key tool used in the development of the regional scale mapping was Viewlog © borehole data management software. This software is designed for the management and analysis of borehole information and for the construction of MODFLOW groundwater models. Once the regional scale mapping had been completed, the mapped information was then used to construct an uncalibrated regional scale MODFLOW model.

The regional scale mapping series includes fifteen different maps. These include:

Physical Setting

1) Quaternary Geology
2) Bedrock Geology
3) Major Moraines (Figure 1)
4) Ground Surface
5) Bedrock Surface
6) Overburden Thickness
7) Sand & Gravel Thickness

Hydrogeology

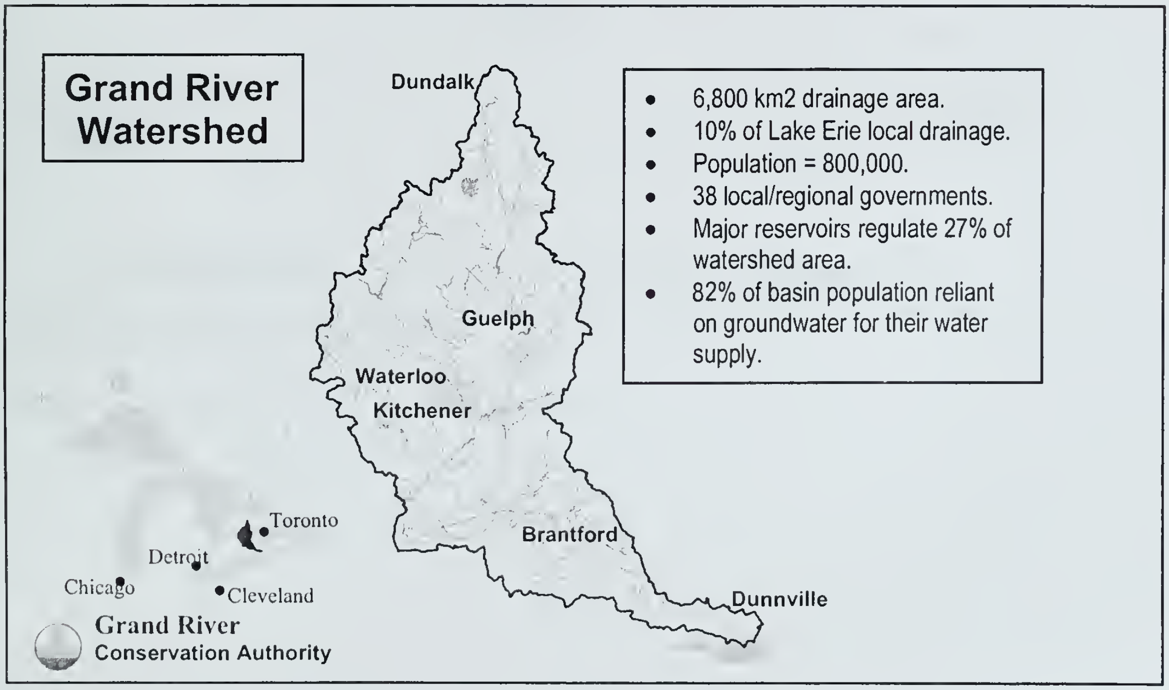
8) Water Table Surface
9) Potentiometric Surface
10) Upward Vertical Hydraulic Gradients
11) Downward Vertical Hydraulic Gradients
12) Depth to Water Table
13) Depth to Uppermost Aquifer

Sensitivity

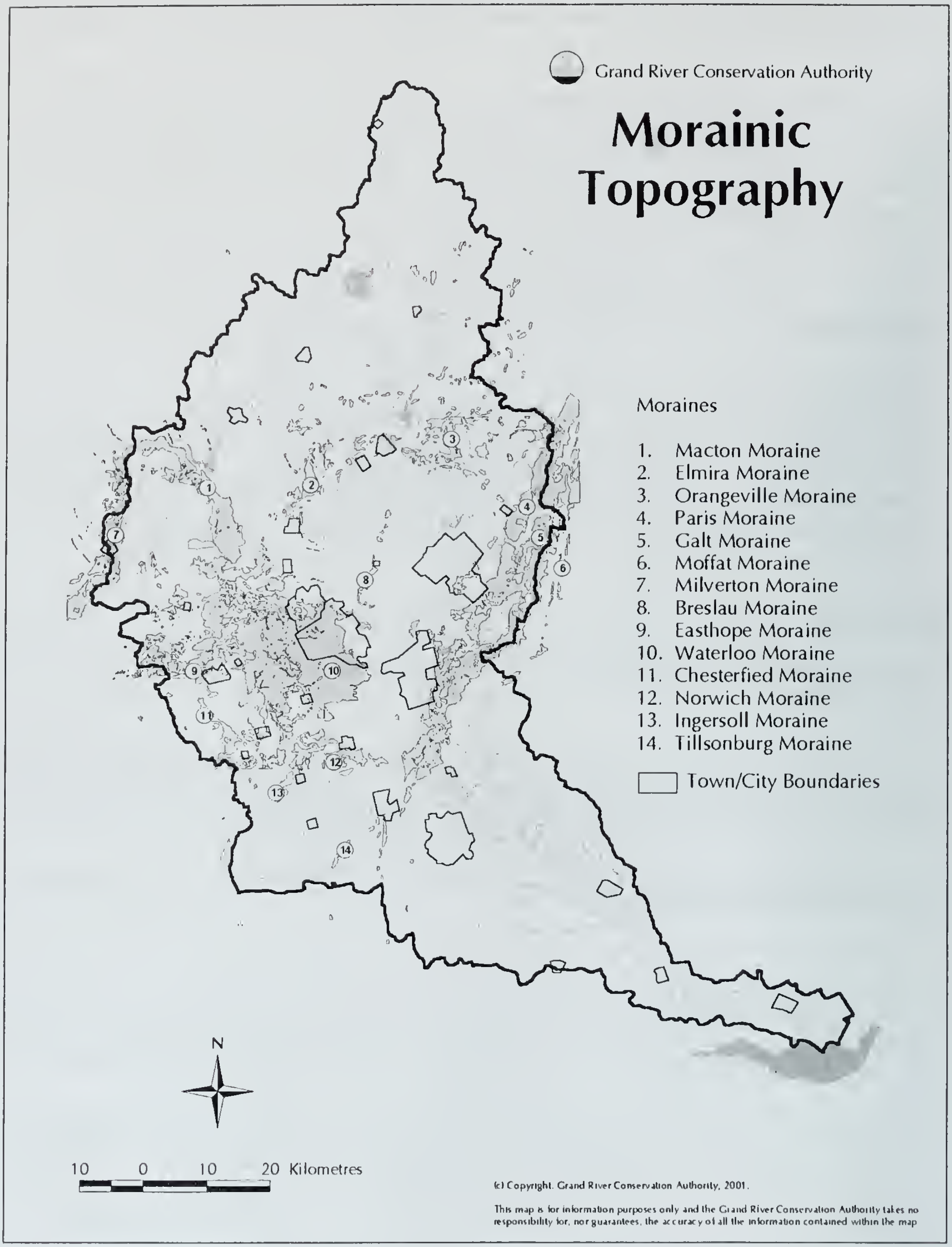
14) Vulnerability to Contamination
15) Potential Discharge Areas

As part of mapping the bedrock surface, bedrock valleys were delineated as is illustrated by Figure 2. Bedrock valleys may represent important controls on the groundwater system and have the potential to serve as excellent sources for municipal water supplies.

All the above maps were used to gain a fuller understanding of how the groundwater system functions throughout the watershed.



- 6,800 km2 drainage area.
- 10% of Lake Erie local drainage.
- Population = 800,000.
- 38 local/regional governments.
- Major reservoirs regulate 27% of watershed area.
- 82% of basin population reliant on groundwater for their water supply.


Grand River Conservation Authority

Morainic Topography

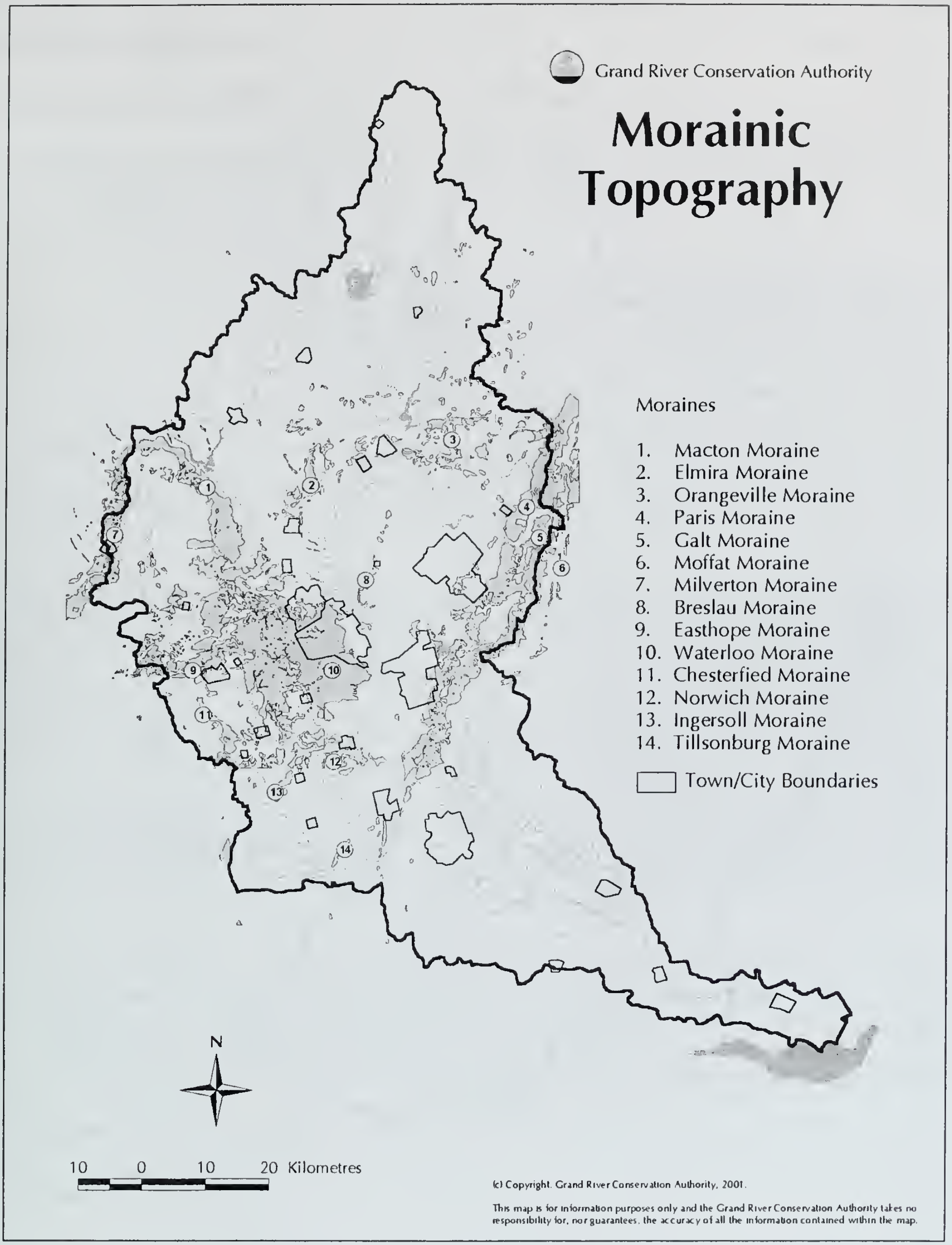


Figure 1. Major moraines of the Grand River Watershed.

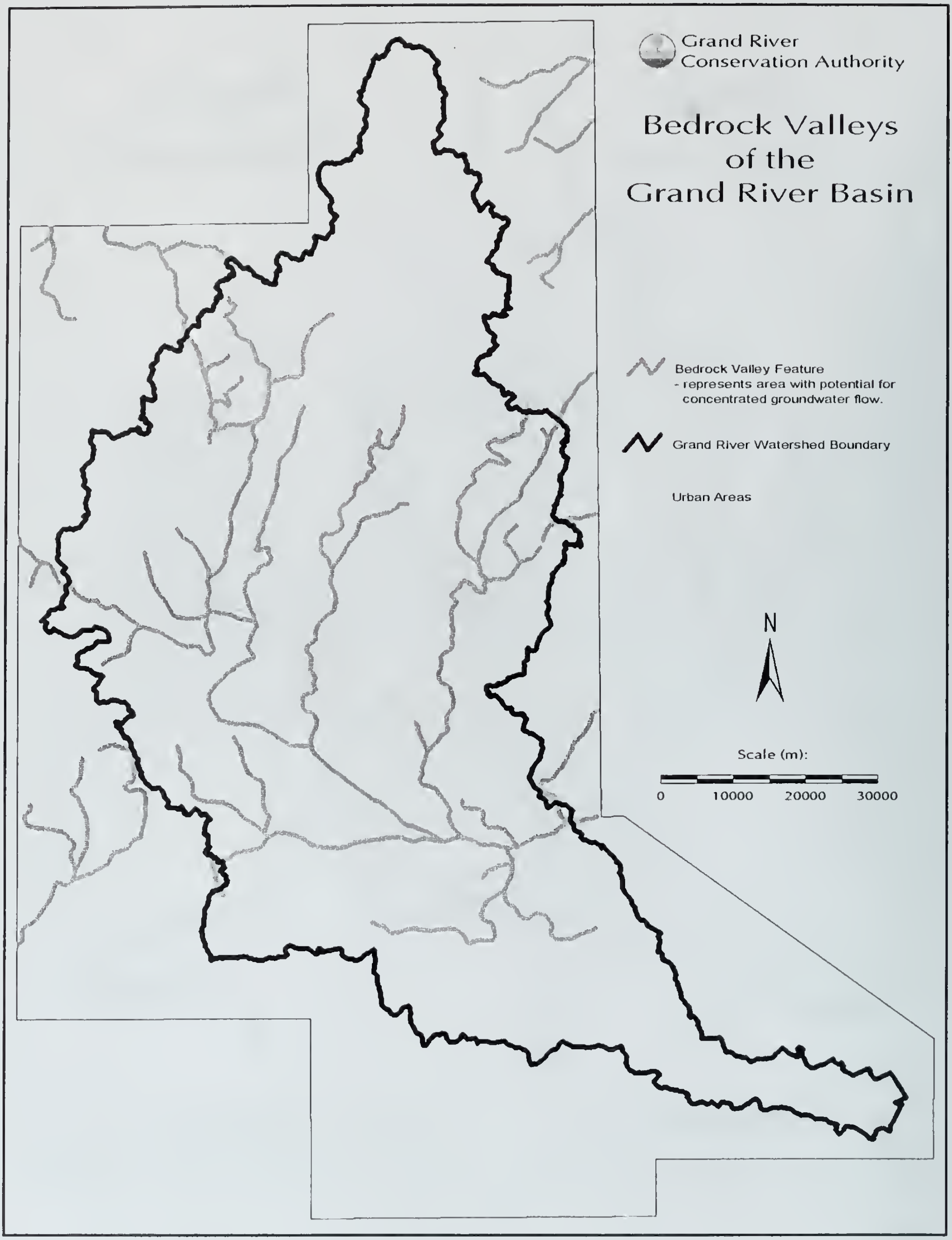


Figure 2. Bedrock valleys of the Grand River Watershed.

Estimating parameters for a complex regional 3D groundwater flow model in southeastern Wisconsin

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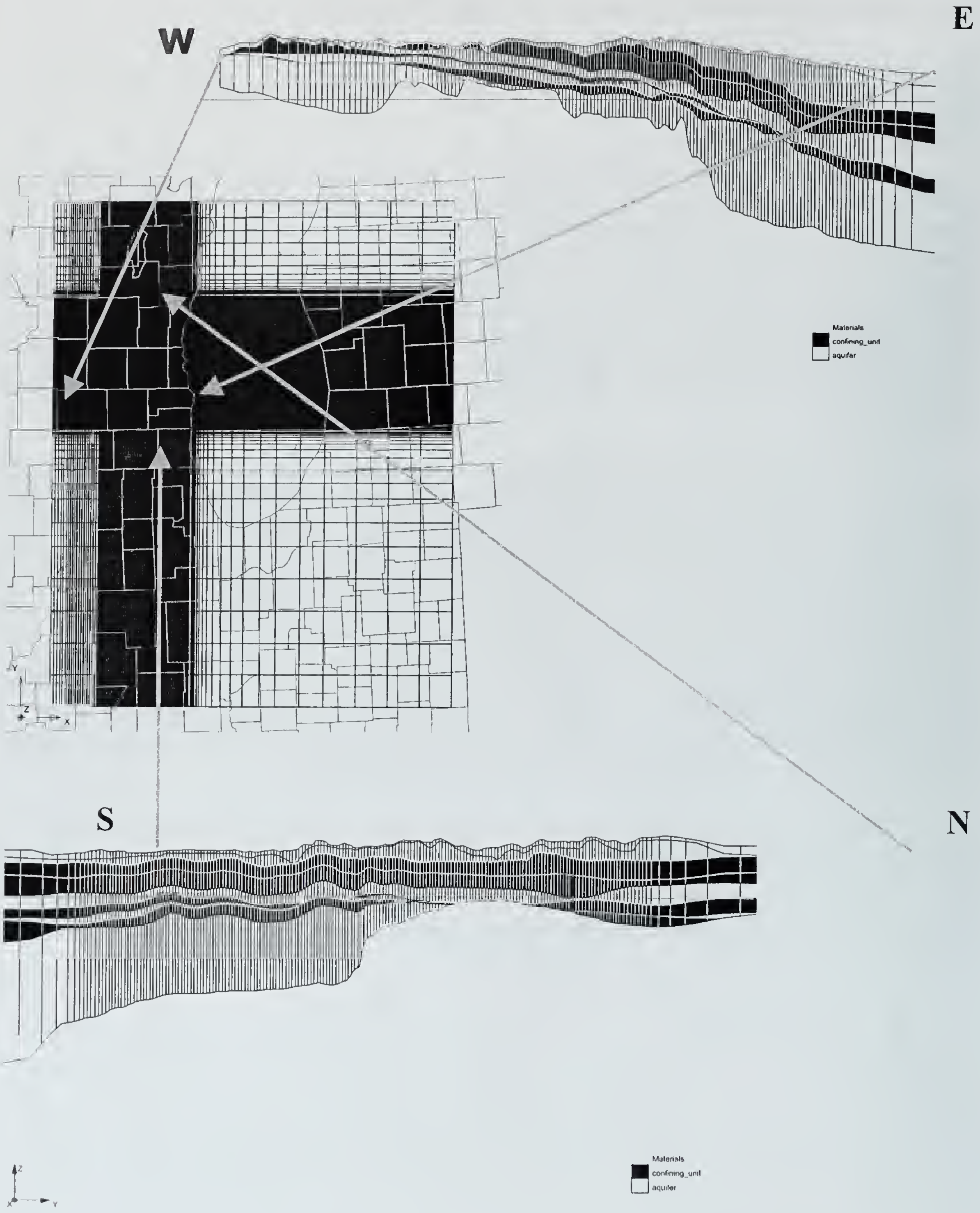
Regional-scale groundwater flow models are increasingly useful for groundwater management across broad areas. Recent regional models in south-central and northeastern Wisconsin have been used to study wellhead protection and multi-aquifer pumping impacts in areas of intense municipal water demand. Computer models complex enough to adequately meet these needs require analysis and synthesis of large amounts of data of widely variable quality. We report on our work constructing a flow model for a somewhat larger area in southeastern Wisconsin, where data include an extensive collection of deep well logs, well constructor's reports, downhole geophysical logs, published well testing reports, and water use records. We are also incorporating GIS coverages of hydrography and surficial geologic and hydrogeologic maps, as well as associated research studies on specific hydrostratigraphic units and recharge estimation.

We have employed some innovative methods to integrate this wealth of data into our conceptual model to honor the complex hydrostratigraphy of the area without incorporating more detail than needed (Figure 1). We used preprocessing software (GMS) to analyze and generate model layer elevation surfaces from well log data, and estimated means and ranges of hydraulic conductivity for different units using specific capacity information. Using lithologic descriptions from well logs, we estimated proportions of fine-grained material for each hydrostratigraphic unit, and combined these estimates with hydraulic conductivity data to derive spatial trends and parameter zonation. For the surficial layer, hydraulic conductivity and recharge zonation from an associated study are being compared with maps from previous work (Figure 2). We are incorporating new data into our model structure from deep well logging (Figure 3) and fieldwork on the Maquoketa confining unit, and will use detailed old water level records from Milwaukee County in the calibration process. Finally, GIS coverages of hydrography have been used to generate complex input for the MODFLOW River Package.

Reliable simulation of regional flow will present additional challenges related to boundary conditions, significant pumpage and transient effects in the confined aquifer system, multiple aquifer well effects, interaction between shallow and deep systems, and direct recharge to the deep system via bedrock valleys. We expect to be able to use this regional model with telescopic mesh refinement for wellhead-protection studies, pumping optimization analysis, and perhaps eventual water-quality and transport modeling.

Figure 1: Far-field regional model domain and near-field cross-sections in SE Wisconsin. Black indicates confining units and white indicates aquifers.



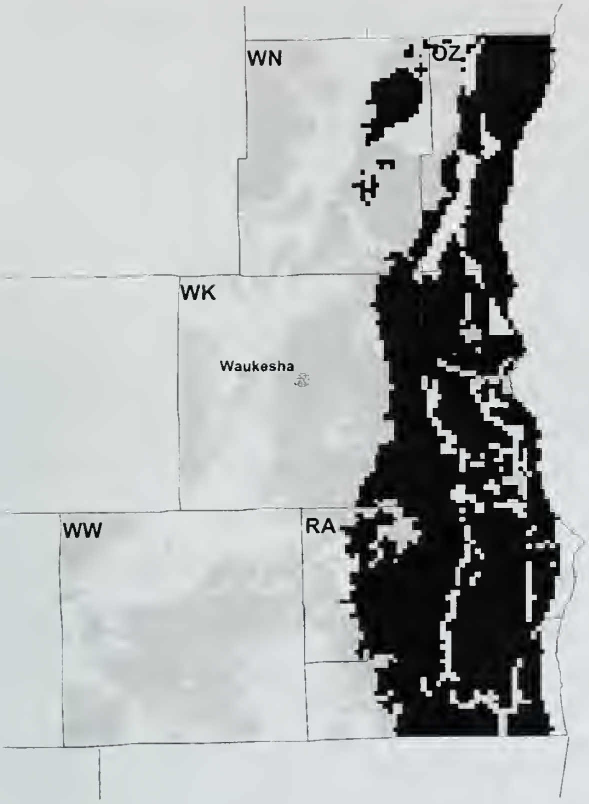


Figure 2: Example of hydraulic conductivity zonation based on Pleistocene mapping

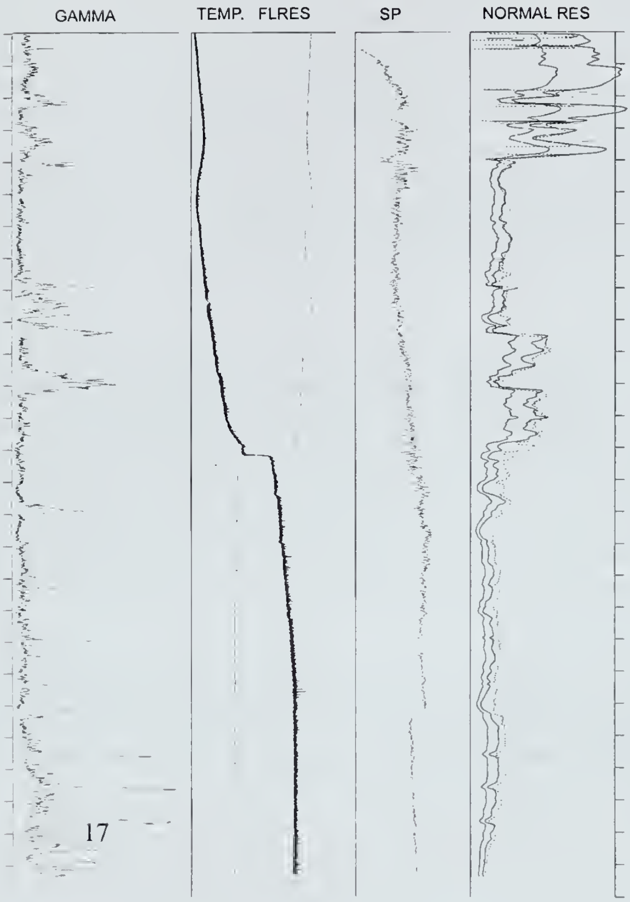
LEGEND

Black: Low K, 0.003 ft/d

Gray: Moderate K, 0.3 ft/d

White: High K, 30 ft/d

Figure 3: Example of downhole geophysical logs from a municipal well in southeastern Wisconsin



A strategy to evaluate soil suitability in the prairie landscape for application of manure

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"Interpreting resource data base information"

The rapid expansion of the livestock industry in Western Canada in recent years, has focused great attention on our soils and water resources specifically, the potential for adverse environmental impacts related to the management and land application of animal manures. To assist in the planning for sustainable development of this industry, a project was funded under the Hog Environmental Management Strategy, (HEMS) to develop standard methodology(s) to assess landscape suitability for manure applications.

The objective of this project was to optimize the utilization of available expertise and resource information data bases, such as soils, geology, hydrology, climate and management, in a standardized format to facilitate systematic and consistent interpretation from one region to another. The resulting information would be accessible using GIS in a decision support mechanism linking appropriate management options to particular environmental circumstances in the landscape.

The development of standardized databases for soils, landscapes and surficial geology required the classifying, categorizing and grouping of this resource information using terms that soil specialists and agronomists might easily comprehend. Each of the resource databases contains hundreds of thousands of individual pieces of information specifically identifying important properties and characteristics of complex materials. The first step was to standardize data terminology, content and structure to facilitate automated accessibility using geographic information system technology. Selected attributes from these data sets were then utilized to calculate numeric indices for each of three key environmental components. Each of these indices was then further simplified by categorization into three classes of high medium and low. Finally the three key factors were integrated into a number of soil management groups (SMGs). In addition to resource data integration, information about manure characteristics and management was compiled for developing manure management plans for each SMG.

The three key environment components included **a Nutrient Factor,** describing the capacity of the soil to retain and supply nutrients for crop production, a **Surface Water Factor**, describing the physical characteristics of the landscape that influence surface runoff, and **a Groundwater Factor,** describing the physical characteristics of soils and surficial geological deposits that influence the potential for leaching of soluble substances to aquifers. The first 2 factors were derived from the pedological database, while the third factor was derived by combining pedological data with geologic data from standardized drill logs. The resultant SMGs, highlight various resource limitations and thus indicate management requirements for sustainable manure applications.

This methodology **does not** provide ratings of good, or bad, suitable or unsuitable, it is not prescriptive of rates or methods of application, but rather it links resource limitations to available provincial management guidelines. This methodology **does NOT** preclude the need for site evaluations. It simply indicates resource circumstances that need to be considered for "land" manure management plans.

This methodology (project) is being developed using three pilot study areas across the prairies, and thus involves agronomic, pedologic, geologic, hydrologic and geotechnical resource expertise and includes participants from each of the 3 prairie provinces, PFRA, NRCan, and Research Branch of AAFC. The next steps in the development and adaptation of this methodology will be to undertake additional field-testing to validate and refine the procedure. This will include application to additional databases for many more rural municipalities combined with field evaluations and discussions with local land managers and resource specialist. This will provide an opportunity to gage the utility and acceptability of this approach by provincial specialists in each province.

The approach described above is simply a tool and a systematic approach to be used for screening or assessing the suitability of soils in the prairie landscapes for the application of hog manure taking into consideration the protection of soil, surface water and groundwater quality. The technology described is generic and therefore should facilitate generalized all-purpose planning for various land use issues involving inputs to the environment.

Acknowledgment

Joint project of Research Branch and Prairie Farm Rehabilitation Administration
Agriculture and Agri-Food Canada

A research project funded by Agriculture and Agri-Food Canada under the Hog Environmental Management Strategy as part of the AAFC research strategy for hog manure management in Canada.

Lithostratigraphy and hydrostratigraphy of the Alexandria moraine, Otter Tail County area, west-central Minnesota

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The Minnesota Geological Survey and Minnesota Department of Natural Resources, Division of Waters (DNR-W) are jointly producing the Otter Tail Regional Hydrogeologic Assessment (OT RHA). The Alexandria moraine trends from northwest to southeast across the study area. It is cored by Rainy lobe deposits that are buried by sediment deposited by multiple advances of the Red River ice stream. Geologic mapping has expanded our understanding of the sequence of surge-like ice advances, their depositional extent, and the hydrostratigraphy of the Alexandria moraine.

Surficial mapping, test drilling, and outcrop examination provided information necessary to interpret the near-surface lithostratigraphic setting. This information included samples derived from Rotasonic cores (3 test holes; ~600 ft of core), soil probe borings (~360 test holes), and outcrop descriptions. Computer assisted interpretation of nearly 900 textural and lithologic sample sets were used to characterize tills. Otter Tail RHA interpretations were combined with the results of the Red River Valley Regional Hydrogeologic Assessment (RRV RHA) and other regional studies to develop the near-surface lithostratigraphic model (Figs. 1 & 2).

Thirteen near-surface lithostratigraphic units were identified and placed in seven groups based on textural and lithologic attributes and stratigraphic position. Four of the groups are present on the surface of the Alexandria moraine, and three are confined to the subsurface.

Eighteen computer assisted regional cross sections were generated from water-well data and surficial geologic maps. Older layers of Rainy lobe till were correlated based on similarities in elevation and the assumption that associated sand layers represented boundaries between successive glacial advances. The presence of oxidized till was also used to delineate till boundaries. Correlations at the intersections of the cross sections were made consistent to create a three-dimensional picture of the stratigraphic setting in the eastern portion of the region.

Using a GIS platform (ARCVIEW) and working interactively with the cross-section network, sand intervals from each well log in the eastern portion of the study area were assigned a stratigraphic label. Sand thickness (or absence of sand) for each well was plotted on separate maps for the three uppermost stratigraphic units. Sand distribution maps were then drawn by hand using a fluvial depositional model (Figs. 3 & 4).

Buried sand distribution maps are useful for understanding well interference problems, water supply problems, and constructing numerical flow models. Surface and near-surface geologic maps are currently being used by the DNR-W to construct conceptual models of groundwater/lake-water interactions and a pollution sensitivity model of the water table

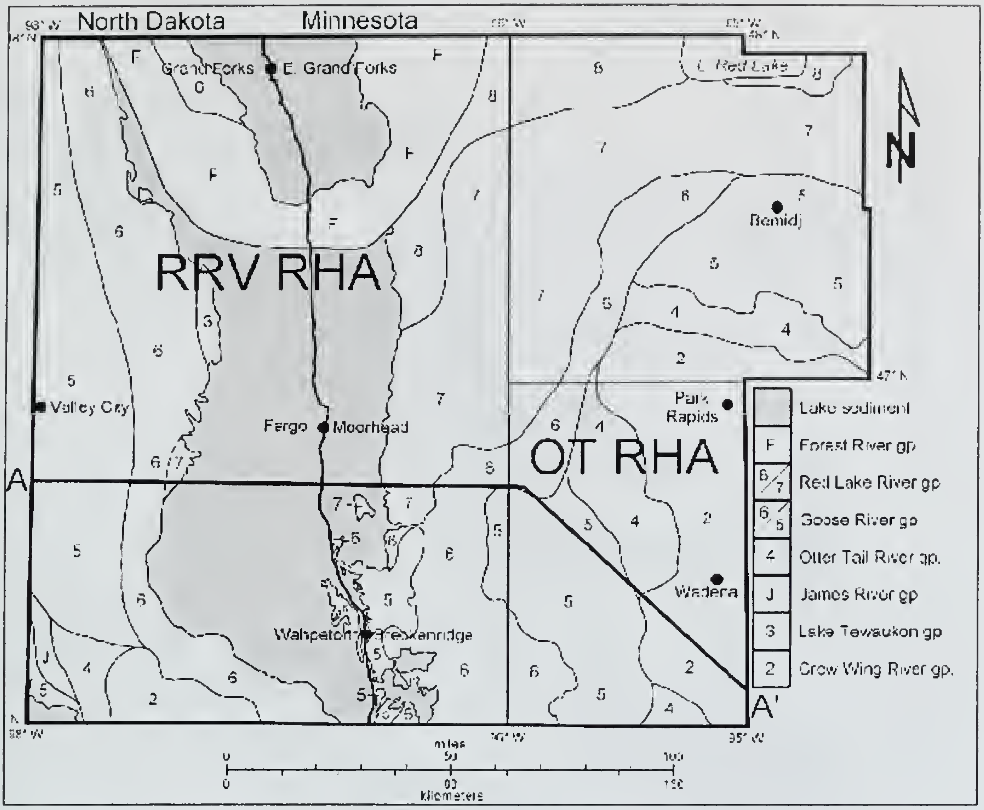
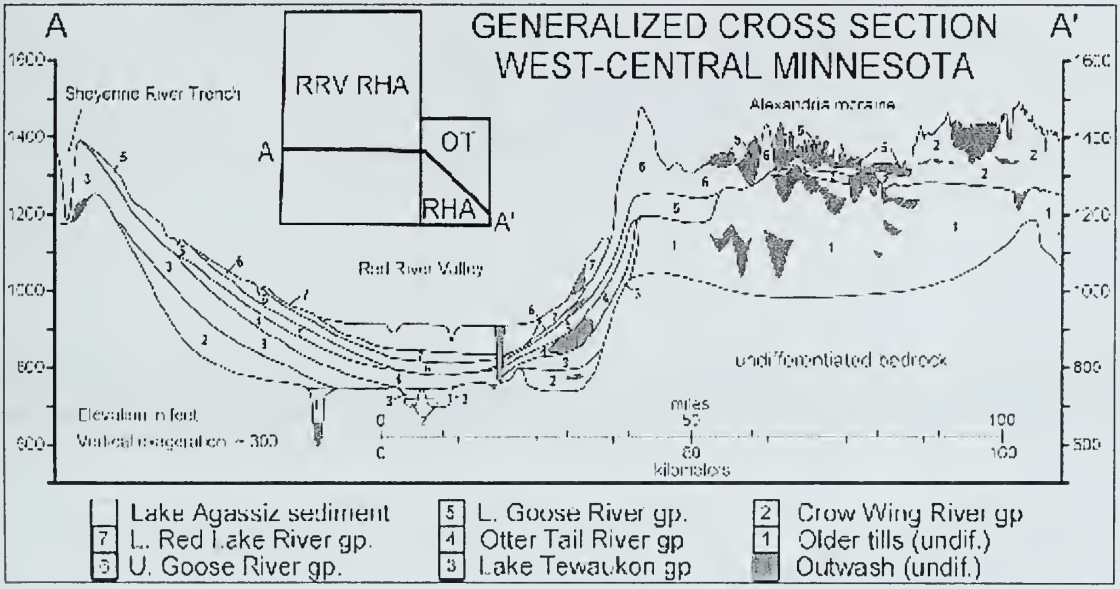


Figure 1. Generalized lithostratigraphic map of the Otter Tail study area, Red River Valley study area (RRV RHA), and adjacent area. Cross section A-A' shown on Figure 2.

Figure 2. Generalized cross section through the Red River valley and Alexandria Moraine, eastern North Dakota and west-central Minnesota.



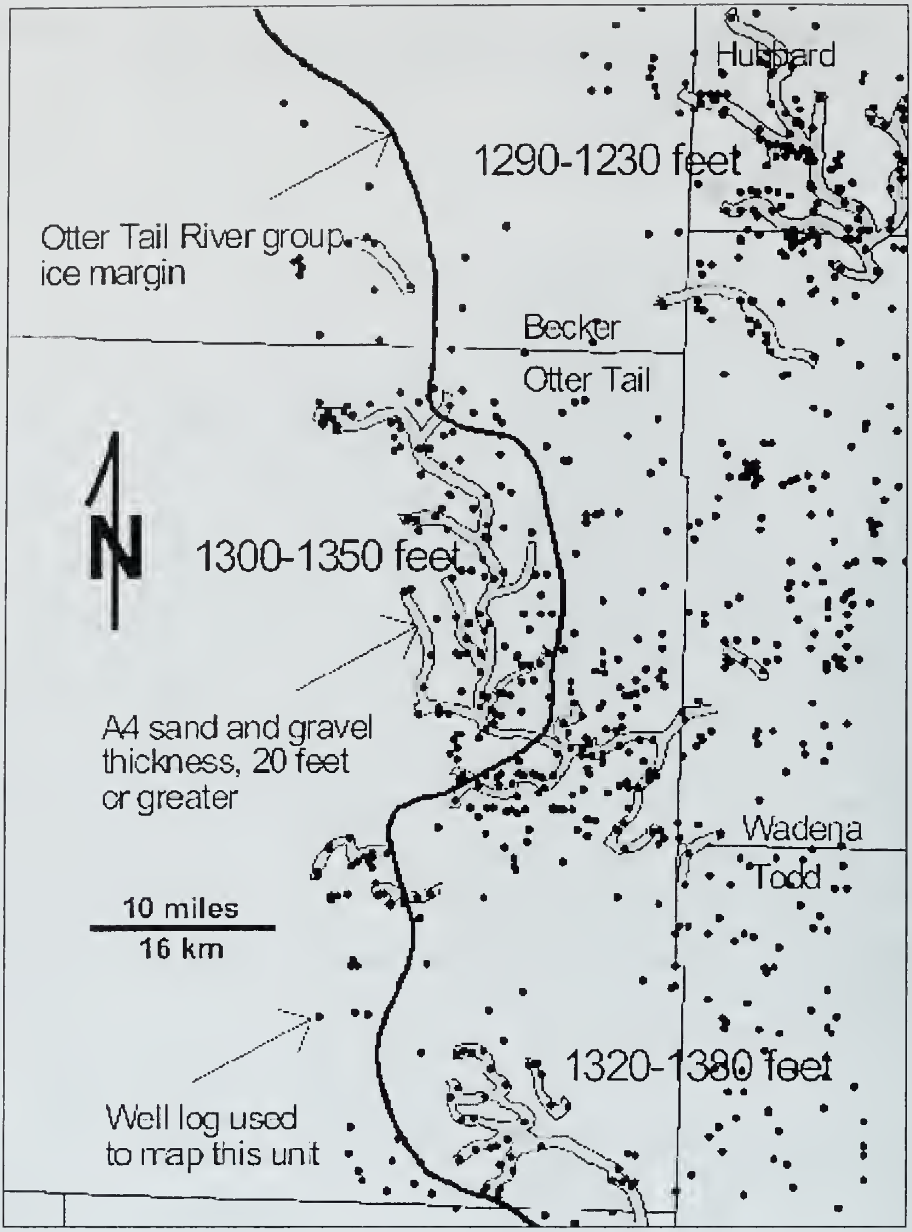


Figure 3. Buried sand and gravel deposits (over 20 feet thick) are shown with the water well records used. Channel complexes occur in the three noted elevation ranges. The Otter Tail group ice margin marks the eastern limit of the northwestern-source drift. Map shows county boundaries in the eastern half of the OT RHA study area.

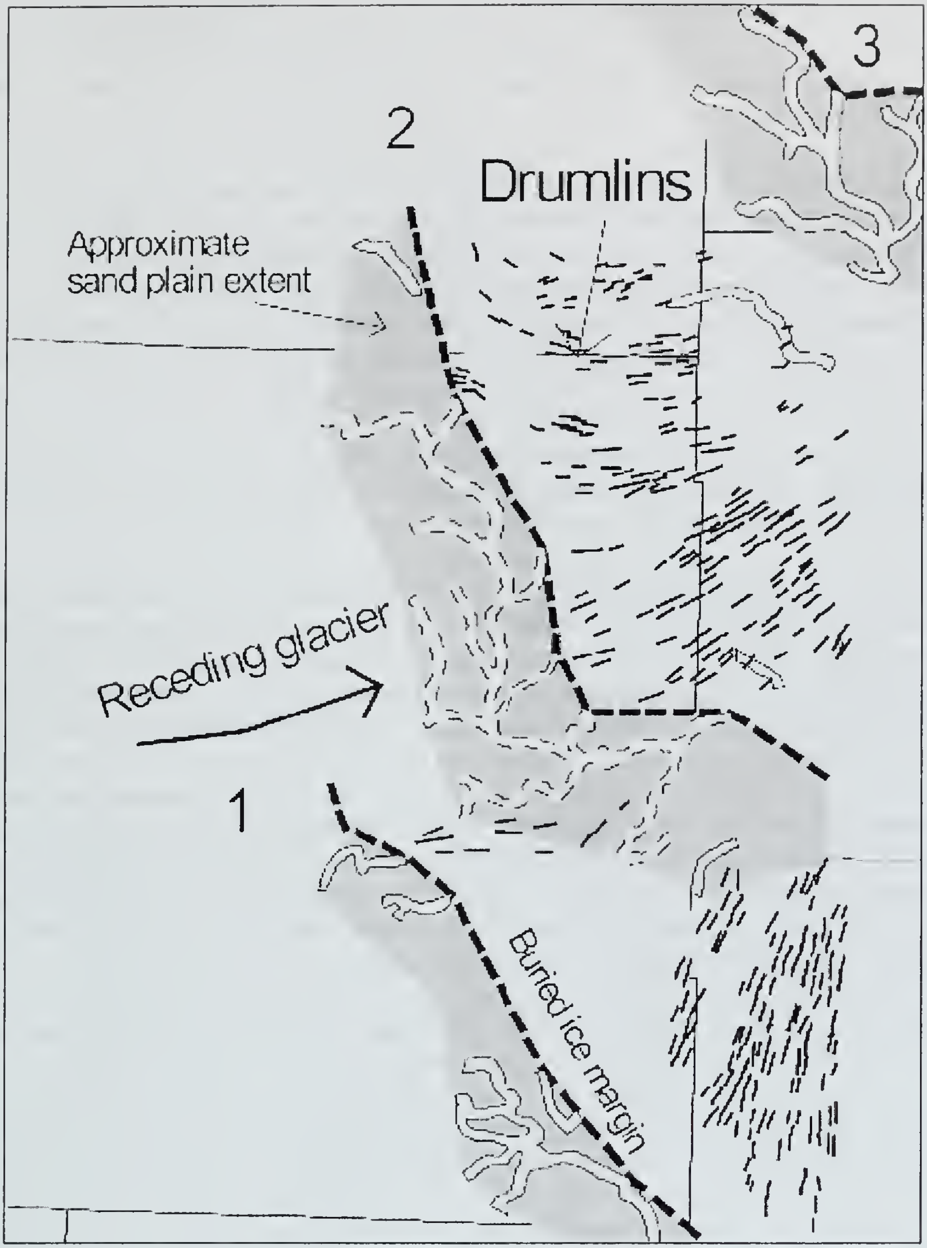


Figure 4. Channel complexes of Figure 3 may have been associated with the sand plains shown. Dashed lines represent possible receding ice margins (1, 2, and 3) associated with the sand plains. Ice margins 1 and 2 match well with the drumlin pattern. Map shows county boundaries in the eastern half of the OT RHA study area.

A method for addressing variable data quality and clustered data

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Large databases, such as the central database at the Illinois State Geological Survey, can have advantages and disadvantages when it comes to creating 2-D and 3-D maps and models of geologic systems. These large data sets can provide valuable insight about changes in materials over short distances. These large data sets, however, typically have areas of very clustered data and can provide too much information for inclusion and display in geologic maps and models. The data also are of variable quality; at one extreme, data are precisely located and accurately described, while data at the other extreme have inaccurate locations and incorrect lithologic descriptions. Verifying the correct location for individual records can be very time consuming and evaluating the accuracy of the lithologic descriptions requires inferences based primarily on the comparability of each record with neighboring data. However, without declustering the data and evaluating the accuracy of the data, it can be very difficult to make geologic models that contain the features that the modeler wants expressed.

Computer interpolation (contouring) software packages typically create surface and volume models that consist of uniformly spaced grid nodes, where a single value (e.g. elevation of a stratigraphic contact) is assigned to each node. The value assigned to each node is typically a weighted average of neighboring data points. For the resulting geologic model to capture the variability observed in the data, the spacings between grid nodes must be smaller than the spacing between data values. In areas of clustered data where the data spacing is smaller than the grid node spacing, grid node values will be determined by a larger number of data points than in areas where the data spacing is larger than the node spacing. When large numbers of data points are used to calculate individual node values, the modeler may need to use more soft data values or make many adjustments to grid files in order to produce surface models with realistic geomorphic and stratigraphic features. In areas with clustered data and large local variability of values, more soft data will be needed to produce models with realistic features than in areas where either local variability is small or data are not clustered.

Methods for addressing the clustering of data depend on how the quality of the data are treated. The data can be viewed as having a relatively consistent problem with errors, where errors are assumed to be unidentifiable but fairly similar between wells. If this scenario describes the data errors, geologic models created using a grid spacing that is larger than the minimum data spacing (i.e. models based on clustered data) should predict the average behavior of the deposits. The data can also be viewed as being variable in data quality, with some records being more accurate than others. If this scenario describes the data errors, then there can be some benefit in trying to create geologic models using only a subset of the data (i.e. declustered data sets); this subset ideally includes only the most accurate and relevant records. The spatial distribution of this subset can be carefully selected so the data have a relatively unclustered distribution, with a minimum data spacing that is larger than the grid node spacing of resulting computer maps and models. Models created with these declustered data sets can be easier to modify, creating surface maps and volume models that are reasonable according to interpretations of the geologist. The difficulty with attaining this idealized data set from a large database can be in developing a method to evaluate the accuracy and relevancy of any given data point.

Using a data set from East-Central Illinois, which contains data of variable quality that is spatially clustered at a scale smaller than the selected grid node spacing, a ranking system is presented for evaluating the accuracy and relevance of geologic data. This ranking system explores the use of five different characteristics of geologic data, including: lithologic value; hydrologic value; spatial importance; driller reliability; and, land-surface elevation reliability. The"Lithologic Value" of a datum is determined using five parameters to evaluate the probable reliability and importance of the lithologic data from each record. These parameters include: lithologic description detail; total depth; purpose of borehole; presence and type of geophysical logs; and, presence and type of samples. The "Hydrologic Value" of a datum is determined using five parameters to evaluate the relative completeness of each well record in describing the hydrology of the materials that the well is constructed in. The "Spatial Importance" of a datum is a measure of the area (or volume for 3-D modeling efforts) that each point represents. This characteristic looks at the clustering around each data point and at the total depth of the hole. Data points that have many close neighbors will have less importance than points with fewer close neighbors. The "Driller Reliability" of a datum is self explanatory and is based on the recognition that some drillers provide more accurate well logs than others. For this factor, the Lithologic Value of well logs are summarized for each driller and compared to the Lithologic Value of well logs from other local drillers.

To use this ranking system, each datum is rated for each of the five characteristics. Then, based on the relevance of each factor to the geologic modeling priorities, the entire data set can be sorted by these ratings. These ratings can be used for exploratory data analysis and for declustering of large data sets. The five component ratings can also be used for more focused explorations of the database. The use of these ratings for exploratory data analysis is demonstrated for a data set in East-Central Illinois. The ratings are used to evaluate the local variability in elevation of specific stratigraphic contacts. The ratings are also used to look at larger-scale variations in these same stratigraphic contacts. Analysis of the ratings of the five component characteristics will also be presented. Finally, these ratings will be used to compare and contrast surface models made from clustered and declustered data sets.

This ranking approach is simple, and ensures that the specific nuances of the data set and the distribution of materials are used to determine the relevancy of the data. The use of this type of ranking-based declustering approach for geologic modeling can allow the modeler to more easily control the features of geologic models. The identification and selection of a more accurate subset of declustered data will reduce the variability of the data sets and resultant geologic models. This type of ranking system also can be useful in early stages of a mapping project. Depending on the spatial distribution and the interpreted relevance of the data, only a subset of records might be selected for locational verification and use in modeling. In projects with large data sets this can result in a significant savings of time and money.

Geological control in 3D stratigraphic modeling, Oak Ridges Moraine, southern Ontario

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The Oak Ridges Moraine (ORM) National Mapping Program (NATMAP) study area is located in one of the most populous regions of Canada. The moraine itself is regarded as a sensitive groundwater recharge area for the Greater Toronto Area. The ORM NATMAP project has benefited from a large amount of archival data and has produced 1:50,000 scale surficial geological mapping covering the 11,000-km2 study area. For stratigraphic modeling, these assets are offset to some degree by the size and complex geology of the area and by the fact that the archival datasets are of variable quality and lack standardized geological descriptions. Newly acquired continuously cored boreholes, seismic reflection data, shallow roadside sites, river and bluff sections as well as archival geotechnical and hydrogeological site investigations are used as control for the model. Approximately 3,800 control boreholes form a clustered coverage that was augmented with more than 50,000 Ontario Ministry of Environment (MOE) water wells. The most abundant and widespread source of archival data in the area, water well records, also contain a wealth of hydrogeological information. However, problems with positional accuracy and clustering needed to be addressed before they could be used in the model. In addition to these problems, the water well drilling process makes accurate depth and textural observation difficult because the well driller must determine sediment textures and depths based on rotary drill cuttings washed to the surface in the drilling fluid. For these reasons, water well data were used with care and only in a supplemental role in areas lacking higher quality data. A 30 m grid-cell topographic digital elevation model (DEM) provided a common reference for all point data (Fig. 1a).

Surfaces representing the tops of the 5 main hydrostratigraphic units in the area (i.e., lower deposits, Newmarket Till, ORM sediment, Halton Till, and glacilacustrine and Recent deposits) (Fig. 1b) are interpolated by combining datasets in a logical sequence. Conceptual geological knowledge derived from traditional field mapping is used to help interpret control borehole data stratigraphically. Control data are used, in turn, to guide water well interpretation and stratigraphic coding (Fig. 1c). Where necessary, zero-thickness intervals were inserted to ensure that the complete stratigraphy was represented in each borehole record (Fig. 2). The model was constructed in the following sequence: 1) training surface interpolation using only control data (Fig. 3a-f), 2) automated MOE water well interpretation, and 3) final surface interpolation combining control data and stratigraphically coded MOE water wells. Both interpolation steps (1 and 3) followed the same process, however training surfaces were Triangulated Irregular Networks (TINs) and final surfaces were made using Natural Neighbour interpolations. For automated water well interpretations, training surface elevations and distances to control points were appended to each water well. Wells located within a 1-2 kilometer buffer from control points were compared to training surface elevation values. The stratigraphic coding of such wells was constrained by an elevation tolerance range that increased linearly from +/- 1 to +/- 10 meters at the maximum range of influence buffer (Fig. 3g). The stratigraphic code of the map polygon in which the well is located and other information based on expert knowledge were also appended. A Visual Basic© program was used to synthesize this information with material coding to interpret each well stratigraphically (Fig. 3h). For each surface, a confidence estimation grid is also produced that is based on proximity and relative quality of nearby data points.

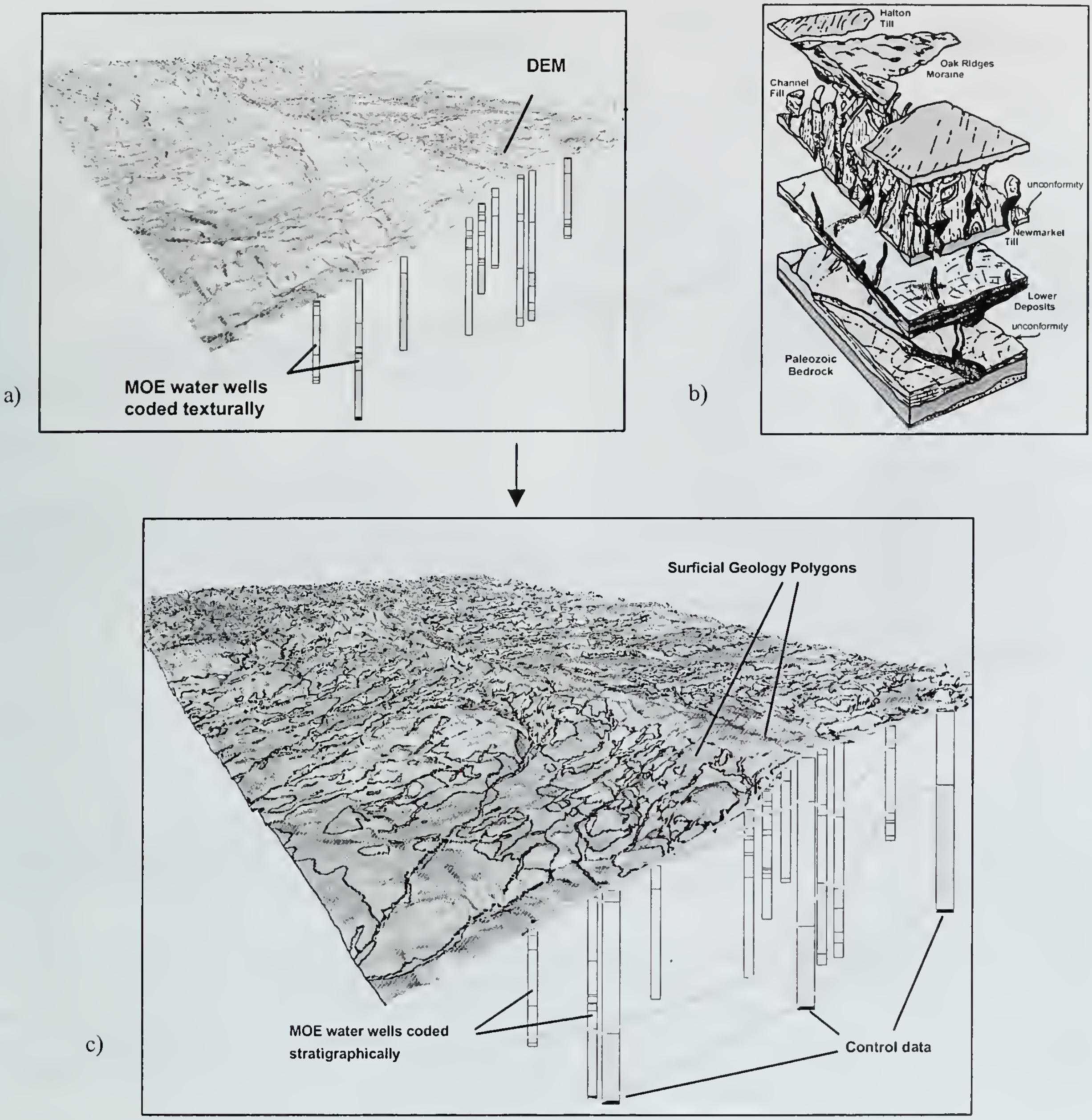
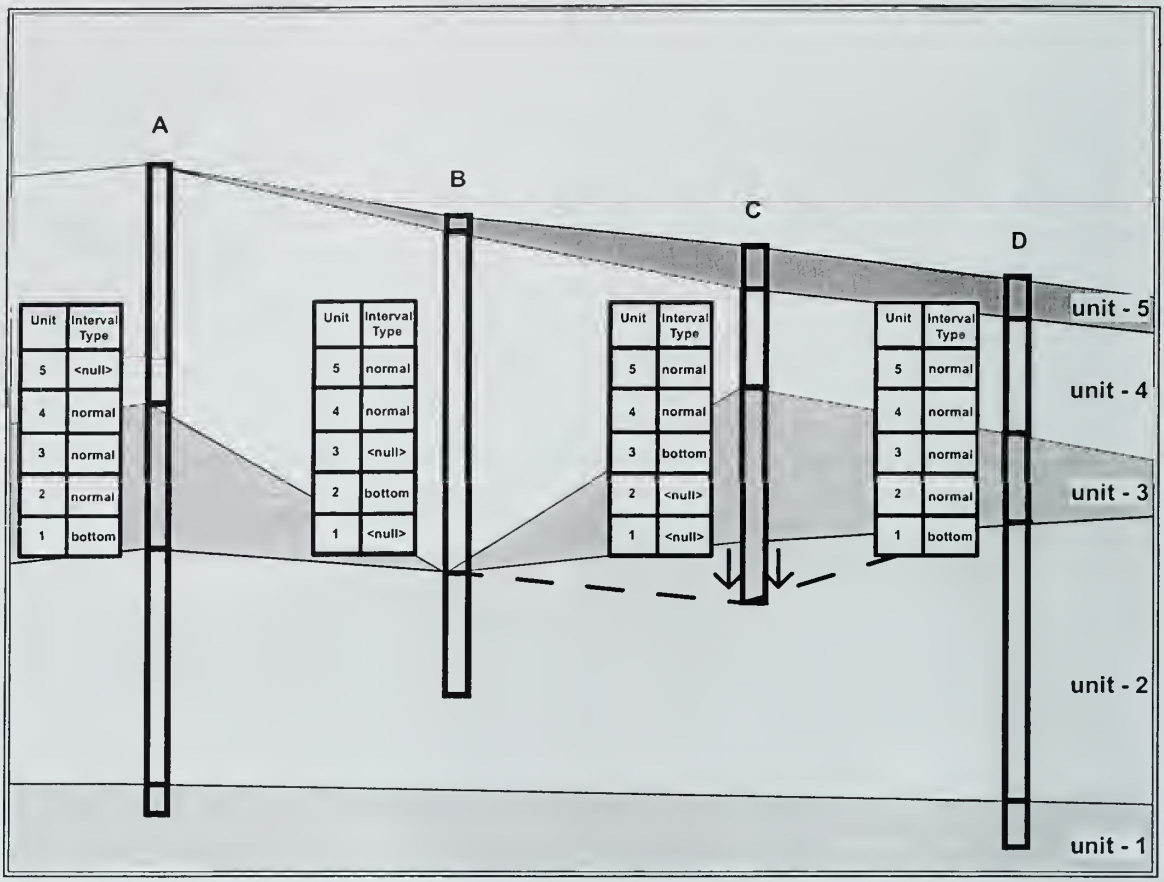


Figure 1. Stratigraphic model development overview a) DEM and lithologically coded borehole data, b) Addition of geological context derived from surficial mapping and control borehole interpretation (Note: uppermost glacilacustrine and Recent deposits are not shown), c) Development of data-driven stratigraphic model with geological control.



Unit	Interval Type
5	<null>
4	normal
3	normal
2	normal
1	bottom

Unit	Interval Type
5	normal
4	normal
3	<null>
2	bottom
1	<null>

Unit	Interval Type
5	normal
4	normal
3	bottom
2	<null>
1	<null>

Unit	Interval Type
5	normal
4	normal
3	normal
2	normal
1	bottom

Figure 2. Examples of borehole unit coding for surface interpolation and for surface correction. Tables represent borehole codes in a database. Borehole A and B both show zero-thickness intervals that can be used to define surfaces (i.e., type '<null>'). The lowest zero-thickness unit in borehole B is located at the bottom of the record and would incorrectly 'pull up' the unit 1 surface therefore such null intervals are ignored. Borehole C shows a condition in which the bottom elevation of the last non-zero interval (i.e., type 'bottom') can be used to 'push-down' the older stratigraphic unit below as indicated. Borehole D has all units present.

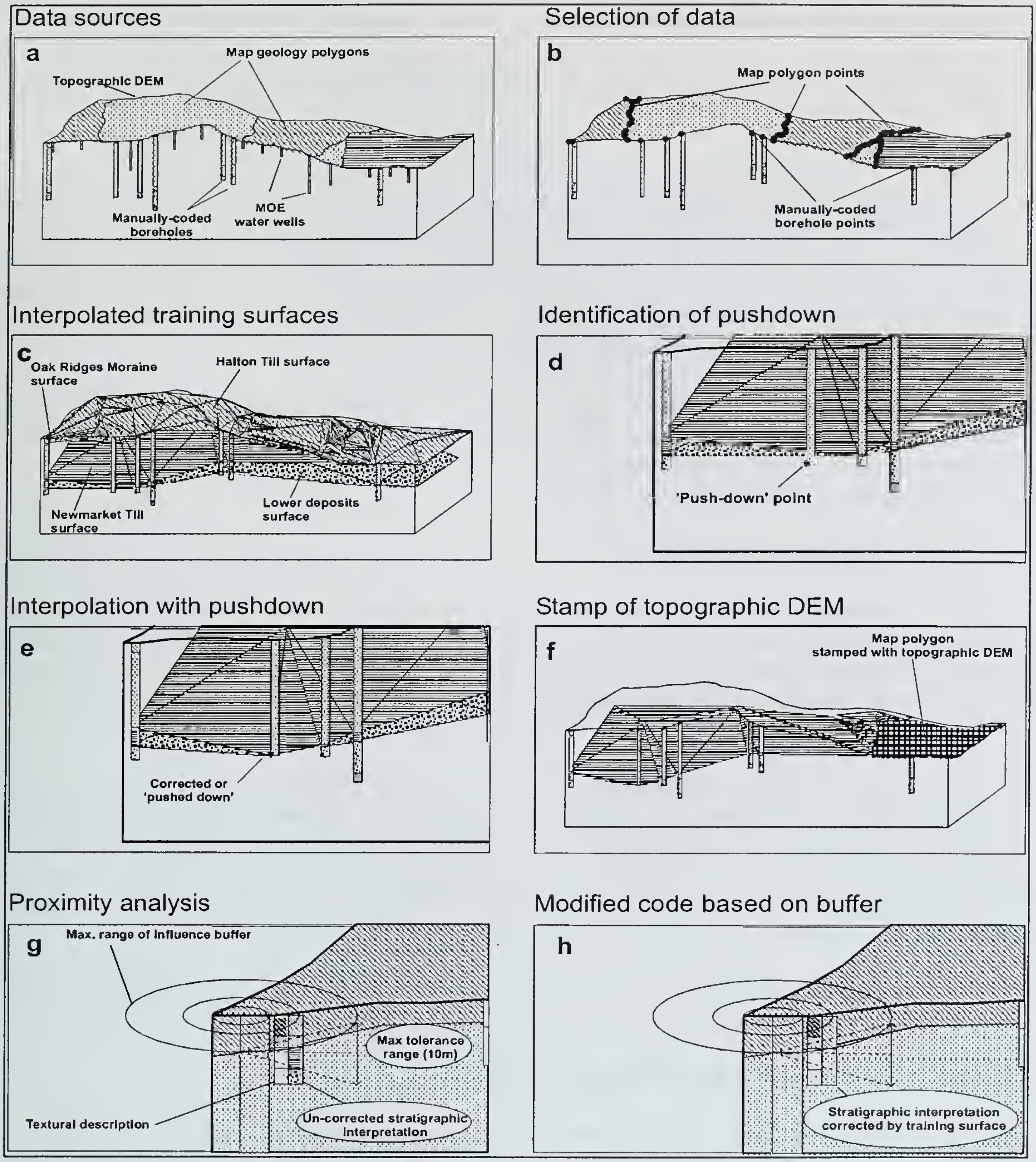


Figure 3. Schematic illustration of the process used to generate stratigraphic surfaces.

Shallow subsurface geological mapping applied to groundwater resource management in Saskatchewan

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Introduction

In Saskatchewan, with its arid climate, water is a scarce and precious commodity. The occurrence of surface water bodies of significant size is limited. Many of these water bodies are not a reliable water source because of inadequate supply and/or water quality. In the absence of reliable surface water, groundwater has, and continues to play, a significant role in the socio-economic development of the Province. As a result, one of the main driving forces behind shallow subsurface geological investigations in Saskatchewan has been the delineation of groundwater resources.

Southern Saskatchewan has been glaciated at least 6 times, and except for its utmost southern part, is covered by up to 300 m of drift (till and stratified deposits). The Quaternary deposits form large flat-lying deposits, which overlie Late Cretaceous (bedrock) sediments. Potable water supplies are found in both the bedrock and Quaternary sediments.

Quaternary Stratigraphic Framework

While the bedrock stratigraphy was well established in the 1960s, this was not the case for the Quaternary deposits. From 1963 to 1972 the Saskatchewan Research Council (SRC) carried out a testhole drilling program which provided the basis for the province's regional Quaternary geological framework. However, it was not until the establishment of the Quaternary stratigraphy in the late 1960's that systematic regional mapping of these sediments was possible (Christiansen, 1968, 1992).

The development of the stratigraphic framework for the southern portion of the province is relatively unique. The framework is based primarily on testhole data rather detailed sections. Mud rotary drilling has been the most common method to investigate the subsurface Quaternary geological conditions. The stratigraphy of the Quaternary deposits is based on the identification of till units. This is done using texture, carbonate content, presence of oxidation zones, single-point electrical resistance characteristics, on electrical logs (E-logs), and geochemical characteristics.

The regional stratigraphic framework forms the basis for site-specific investigations related to water-supply, geo-technical and environmental studies.

History of Subsurface Geological Mapping Program

In response to the need to characterize and manage the groundwater resources, the Province, through the Saskatchewan Research Council (SRC), has prepared geology and groundwater maps since the mid 1960s. From the onset it was realized that mapping of the Quaternary hydrostratigraphic units needed to be based on stratigraphy rather than lithology.

The first generation of geology and groundwater maps was produced during the period from the mid 1960s to1980. A total of 23 maps at a scale of 1:250,000 were prepared for southern Saskatchewan. These maps show the bedrock geology and surface topography. Each map is accompanied by four cross sections. Bedrock and regional buried-valley aquifers (predominantly occurring between bedrock and the first till) are identified but the aquifers within the drift are not differentiated.

When Quaternary stratigraphy was established in the late 1960s and applied on a regional scale, it was possible to map aquifers and aquitards within the drift by stratigraphic context. A new generation of geology and groundwater maps by NTS map sheet was initiated in the mid 1980s, using the "stacked-layers" approach to depict the various hydrostratigraphic units within the drift and shallow bedrock. Digitized groundwater maps and associated geological cross sections are now being produced. The location of as many as 20 cross section lines is based predominantly on the distribution of testhole sites for which an E-log (electric log) and geologist log is available. These cross sections establish a three-dimensional picture of the regional hydro-stratigraphic setting. The regional mapping approach does not allow for mapping of small aquifers. These "local" aquifers are important, however, since many communities in Saskatchewan depend on them for their water supply. Site-specific mapping is required to delineate these local aquifers.

A third generation of maps is planned which will utilize GIS and web-site technology to assist with updating, increased public access, visualization, data interpretation and thematic mapping. Digital geology and groundwater data are increasingly used for the preparation of thematic maps, which are used in the development, management, and protection of groundwater resources.

Construction of a stack-unit map to predict pathways of subsurface contaminants within the A/M Area of the Savannah River Site, SC

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In the mid-1990's, contaminants were detected in the aquifer zone from which the U.S. DOE's Savannah River Site (SRS) in South Carolina produces their potable water. To help delineate the probable pathways of the detected contaminants, the SRS requested an examination of the hydrostratigraphy of the interval overlying the contaminated portion of the aquifer, the Crouch Branch aquifer. A stack-unit mapping approach was used for this problem. This approach utilizes a Geographic Information System (GIS) to integrate subsurface geologic data, soils data and hydrologic data to create a contamination potential map. The interval, which overlies the Crouch Branch aquifer, consists of 10's of meters of vadose and over 100 m of saturated zone with three aquifer and three confining units. A total of 174 borings, all with detailed descriptions, some samples, and precise locations were used within the approximately 20 km^2 study area (the A / M area).

Computer-drawn isopach maps of the six units were produced using GIS capabilities. First, seven contour line coverages (from the land surface to the top of the Crouch Branch aquifer) were entered by the topogrid interpolation methods for the creation of Digital Elevation Models (DEM). Separate grids for each of the six data layers were generated. All elevation determinations on logs from bore holes were scrutinized carefully by evaluating how well they agreed with known depositional and structural models of the study area. Elevation data that did not agree with trends of data were discarded and elevation contour maps for all units were modified accordingly. Deviant data usually consisted of data from old log descriptions that were not performed under a quality assurance program or the data were determined to be of questionable interpretation by site geologists.

A 5 m resolution was chosen for each grid to capture the total detail. The Arc/Info® GRID module was selected for further processing of grids with each of the isopach grids converted into Arc/Info® polygon coverages. Elevations from vertically adjacent upper surfaces were "machine-subtracted" to create six isopach maps. It was important to derive computer-drawn isopach maps because the maps revealed previously undisclosed features. However, the subtraction process resulted in many of the computer-drawn maps not appearing geologically plausible. Revised isopach maps then were made for each unit by overlaying individual thickness points on the computer-drawn maps and redrawing the maps. These revised maps retained the original unbiased computer-drawn surfaces, honored specific thickness data points and trends of data, and produced a more geologically sound representation of the three-dimensional geology that was more in keeping with known depositional and structural models.

An additional variable, besides thickness, that was pertinent to the shallowest confining unit, the Green clay, was the presence of sequences with vertical conductivities equaling those of the overlying aquifer unit. These intervals were identified by their high leakance values. Consequently, the stack-unit map created by stacking polygon coverages of the six isopach maps also included a leakance distribution map of the Green clay confining unit.

The "stacking" process in GIS is known as a "*spatial join*" and is accomplished by an overlay procedure that is fundamental to GIS spatial analysis. The attributes for the polygons in the resulting stack-unit map consist of composite attributes from the separate unit maps within the stacked-unit polygon. The unedited stack-unit map of the A/M Area contained 1267 polygons with over 600 unique attribute combinations. After editing to remove sliver polygons (those less than 1000 m^2) and dissolving other small polygons into more important adjoining polygons, the final stack-unit map was composed of 341 unique combinations in 455 polygons.

To arrive at a relative contamination potential for the study area, the 341 unique combinations of hydrogeologic sequences and thicknesses were rank ordered, based on their hypothesized potential to retard downward transport of contaminants. The ranking process employed was a logarithmic approach called "utility theory" which assigns each unit an order of magnitude corresponding to its ranked importance. For example, the Green clay confining unit, the most important unit, was assigned a magnitude of 10^5 and the lowest ranked unit (an aquifer with high vertical conductivity) was assigned a magnitude of 10^0 . For the areas that fell within the zones of high Green clay leakances, the mechanism used to arrive at a logical scoring was multiplying the Green clay score by 10^{-3} which resulted in a numerical ranking with the same magnitude as the overlying aquifer unit (10^2).

The distribution of one of the main contaminants, *tetrachloroethylene* (*PCE*), within the Crouch Branch aquifer in the A / M area, correlates well with the contamination potential map constructed using the stack-unit mapping approach described above.

On the construction of 3D geological models for applications in regional hydrogeology in complex Quaternary terrains of eastern Canada

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Predicting spatial variation of hydrogeologic parameters requires a prior knowledge of the subsurface lithology, stratigraphy and architecture of the geological units in a study area. This is particularly true in the complex glacial and glaciomarine terrains of eastern Canada. However, the work required to transform a qualitative knowledge-based geological model into a full 3D geological model and then into a numerical format for input to groundwater flow models is by no means trivial. These models are based to a large extent on inferences from scattered information integrated in datasets, which come from many different sources with their own errors and uncertainties. This problem is magnified by the lack of standards and by the large size of archival datasets, which have been assembled in vastly differing contexts and which, may have undergone several transfers from one format to another. In spite of these difficulties, integrating this information is a necessity, especially in regional-scale investigations where the high cost of acquiring new subsurface data is a major issue. Thus, there is a need to qualify information according to source so that it can be appropriately weighted in the typically subjective interpretation process.

Since all borehole data are not considered to be of equal reliability, they are assigned a weighting factor using a step-by-step data management approach (Fig.1A-B). This allows to assess the spatial distribution of the data reliability and to evaluate the need for further investigation. Zones of similar predicted reliability are then delineated and taken into account during model construction as well as during numerical calibration process (Fig.2). We are also testing an experimental standard code to integrate data from different sources and with different descriptive attributes (Fig.3). It is also critical that the geologist interpretation be maximized throughout the entire process of model construction. To achieve this, the construction of the model begins with the preparation and interpretation of a series of closely spaced geological cross sections. This is followed by the subsequent extension and correlation of these 2D interpretations in the third dimension to complete the model (Fig.4). The delineation of the irregular volumes is therefore based on the interpreted sections honoring key control points. The final 3D representation of the geologic architecture is controlled by the interpretive input of the geologist as well as by careful use of weighted data. These irregular volumes can then be filled with tetrahedrons. At this stage, the 3D model can be already transferred in a format suitable for the relevant end-process technology, such as finite-element modeling to resolve complex groundwater flow problems. Predefined hydrostratigraphic units can be used to combine irregular volumes with similar hydraulic properties in order to reduce the number of elements and boundaries without affecting model accuracy.

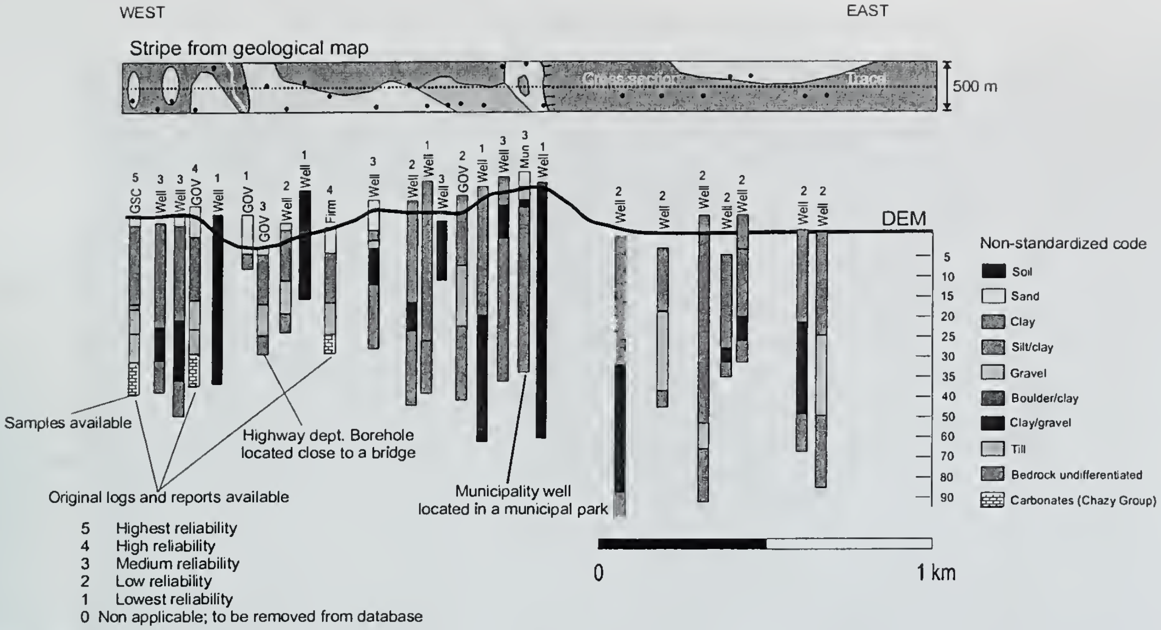


Figure 1. A) Series of computer-generated borehole logs initiating the database validation and integration process along a cross section. This example shows a cluster of borehole logs with contrasting and conflicting stratigraphy. The first step is to integrate newly acquired information from field surveys. The second step is to verify logs for which we have access to original field notebooks and/or reports and/or maps. The next step is to integrate all borehole data whose location and originator are considered as reliable. After comparison with any other relevant information, such as geological maps and DEM, a relative weight based on reliability is assigned to each borehole. Notice that reliability is still low in the eastern portion of the section.

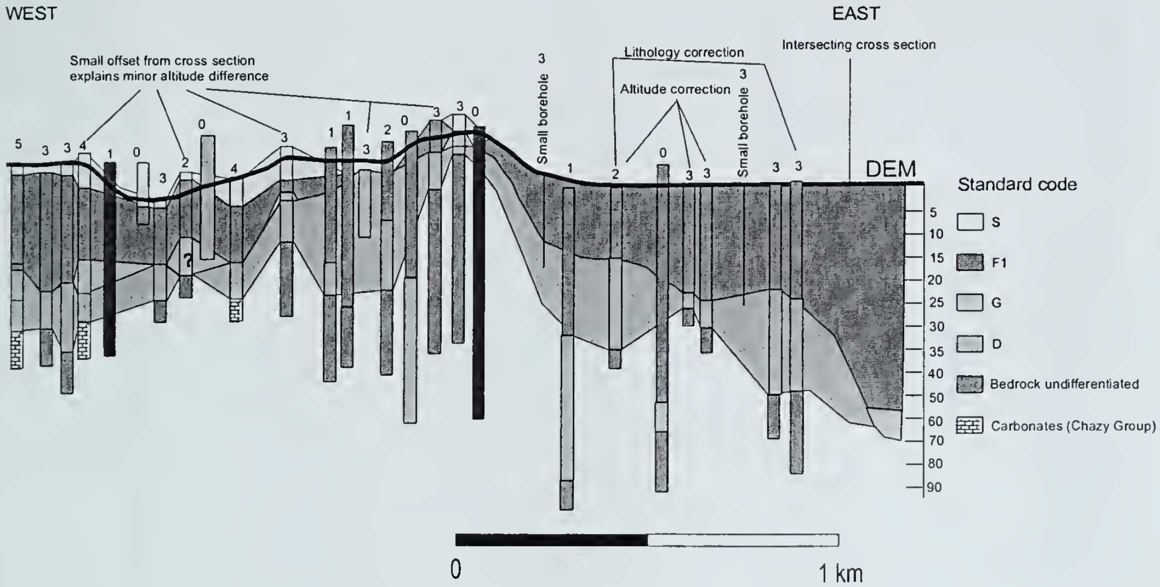


Figure 1. B) Same cross section after field verification using a portable drill to investigate the upper units and after comparison with newly-built orthogonal cross section based on high resolution seismic and high quality boreholes. Logs may be assigned a lower or higher reliability value as a result of this procedure. This is an iterative process where reliability is continuously reevaluated as new information or better understanding of the 3D geology contributes to data validation and model construction.

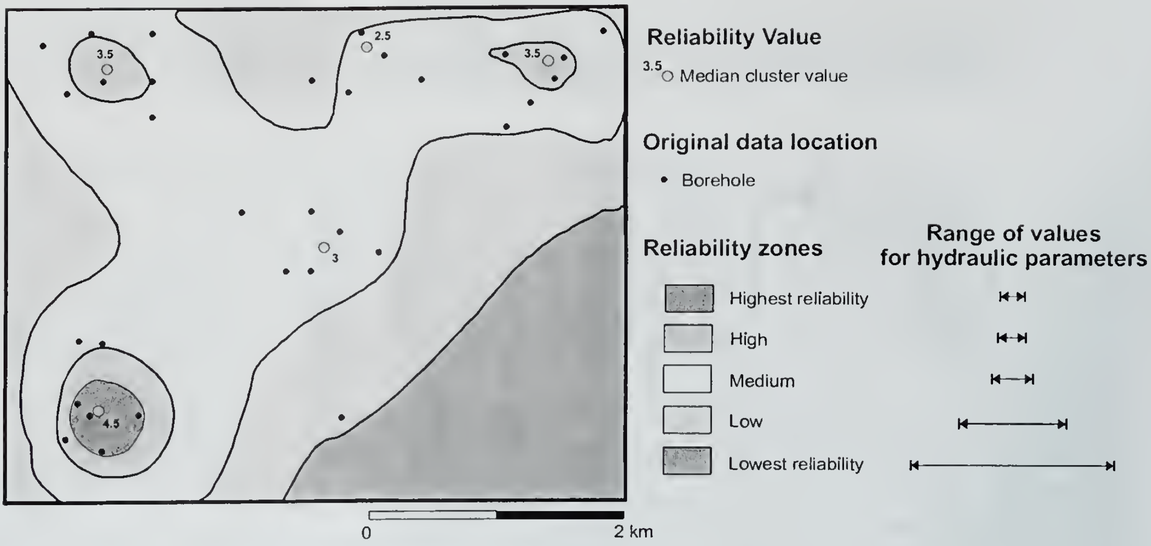
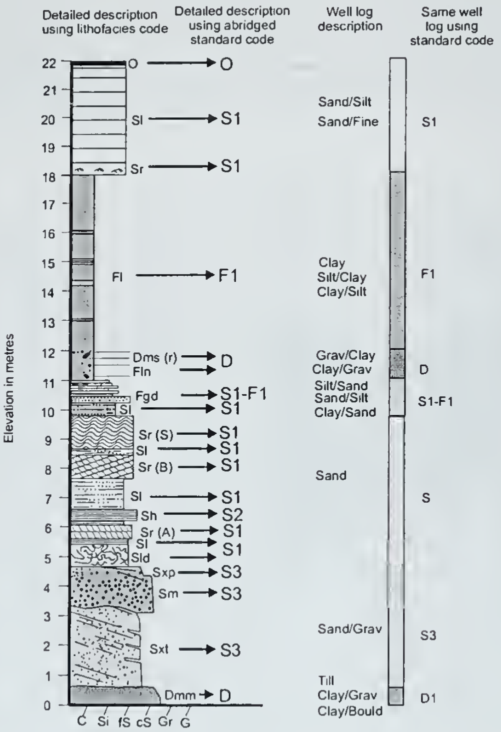


Figure 2. Spatial distribution of data reliability showing homogeneous zones (large scale example). These zones can be used to define groups of elements (i.e. tetrahedrons, cells) for which hydraulic parameters must vary simultaneously within a given range for a given unit during each calibration run of the groundwater flow model.



Sediment	Non-standard. Code	Standard code
Fill	Fill	X
Organics	ORG	O
Till/Diamicton	Till	D1
Clay and Gravel	Clay/Grav	D1
Silt and Boulders	Silt/Bould	D1
Silt and Gravel	Silt/Grav	D1
Sand and Boulders	Sand/Bould	D3
Gravel and Clay	Grav/Clay	D
Gravel and Silt	Grav/Silt	D
Gravel and Boulders	Grav/Bould	D3
Clay	Clay	F1
Silty Clay	Silt/Clay	F1
Sandy Clay	Sand/Clay	F1-S1
Silt	Silt	F1
Clayey Silt	Clay/Silt	F1
Sandy Silt	Silt/Sand	F2
Sand	Sand	S
Fine Sand	Fine/Sand	S1
Medium Sand	Med/Sand	S2
Coarse Sand	Coarse/Sand	S3
Clayey Sand	Clay/Sand	S1-F1
Silty Sand	Sand/Silt	S1-F1
Gravely Sand	Grav/Sand	S2(3)-G1(2)/D
Gravel	Grav	G
Fine Gravel	Fine/Grav	G1
Medium Gravel	Med/Grav	G2
Coarse Gravel	Coarse/Grav	G3
Sandy Gravel	Grav/Sand	G1(2)-S2(3)/D3

Figure 3. A standard code is being implemented to facilitate correlation between highly detailed descriptions using lithofacies code and non-standardized poorly detailed descriptions. This abridged code is particularly useful when systematic distinctions, such as coarse/fine sand, are needed. Three sets of codes are integrated in the standardized database and can be visualized simultaneously.

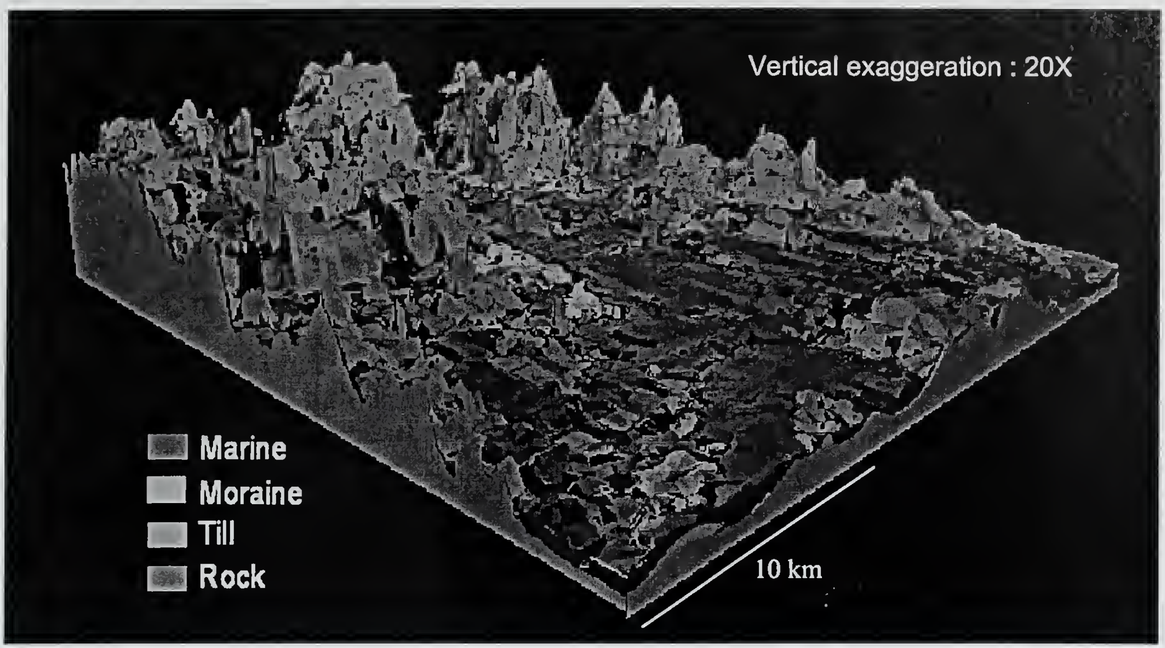


Figure 4. A 3D geological model showing some units from the Laurentian Piedmont hydrogeology project. 41 geological cross sections were digitized and a planar topology was built using ArcInfo™ and georeferenced in 3D. The 3D model was constructed with a *shape base modeling* technique used in medical imagery implemented in GEOSOLID II. The 3D space between sections was filled by matching pixels from parallel planes to form end-members of linear series, then the space between two corresponding pixels is filled with intermediate values. Shades of gray, used in medical imagery, are replaced by a value indicating whether a pixel lies inside (positive) or outside (negative) a geological polygon. This value is the calculated distance from a point to the polygon's border. The space between planes is filled by linear interpolation of distance from plane to plane; the border of a calculated volume being distance = 0.

Not without sedimentology: guiding groundwater studies in the Oak Ridges Moraine, southern Ontario

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The Oak Ridges Moraine (ORM) area in southern Ontario is an ~11,000 km^2 region that houses the largest urban population in Canada (Fig. 1). Groundwater continues to be an important resource, not only for rural households, but also a number of small cities (e.g., Newmarket), agriculture and recreation. Prior to 1993, regional municipalities, government agencies and industry had completed numerous site-specific studies but no regional framework existed within which these local studies could be integrated. A regional geological - hydrogeological study was initiated by the Geological Survey of Canada to establish a 3-D stratigraphic and hydrostratigraphic framework. A basin analysis methodology involving sedimentology, geophysics and hydrogeology was adopted. Sedimentological models were used to improve geological understanding of the area in the following ways: i) stratigraphic architecture, ii) material and stratigraphic coding of archival data, iii) event sequence concepts, iv) depositional facies models.

A conceptual model of the stratigraphic architecture was developed based on regional knowledge and current understanding of glacial processes (Sharpe et al. 1996). This model was used as a working hypothesis that was tested through geological mapping, drilling, seismic reflection profiling and sedimentology. Integration of archival water well, geotechnical and hydrogeological data was an objective of the study due to the abundance of these data and their common use by consultants. Low reliability of primary descriptions, poor resolution of individual units, and lack of sedimentological information were common problems with archival data (Fig. 2). A particular problem was the absence of descriptions of diamicton (till) in the ~50,000 water well records. In contrast regional mapping indicated that ~22 % of the area had diamicton exposed at the surface. To facilitate integration of these disparate archival datasets and improve the geological integrity a common coding scheme was developed (Russell et al. 1998). Two recoding techniques, First Attribute Method (FAM) and a Rule Based Method (RBM) were applied. FAM uses only the first of three attributes whereas RBM uses all three attributes and integrates sedimentological knowledge of the basin. The integrity of the coding system was tested by comparison of the first unit in archival borehole data with the surficial geology map (Fig. 3). The RBM performed more convincingly than FAM in all integrity checks. The sedimentological data was then used to constrain stratigraphic coding of ~25,000 archival data points. Regional stratigraphic surfaces were then interpolated within a GIS (Logan et al., this vol). The composition of the Oak Ridges Moraine was assessed using the archival and sediment facies data (Fig. 4). In common with field experience, this comparison indicates that archival data over-report fine-grained sediment, often by an order of magnitude (Fig. 4a). Comparison of estimates from continuous core with water well data indicates that clay is over estimated by ~30% - at the expense of fine sand. Such erroneous reporting has serious implications when considering aquifer yield or when mapping aquifer vulnerability.

Using sedimentology knowledge, a depositional model of the moraine was developed that defined the spatial and stratigraphic relationships of the moraine and tunnel channel fills. This model defines significant differences in fill geometry and sediment facies compared to more traditional and broadly described alluvial valley-fill succession. A subaqueous fan depositional model is one depositional element of the ORM that permits estimates of flow unit distribution, geometry and thickness at a more detailed scale (Fig. 5).

Conceptual geological models of stratigraphic architecture and depositional facies can provide regional groundwater studies with much needed control and guidance toward development of improved hydrostratigraphic models, understanding of spatial heterogeneity, and improved predictive ability.

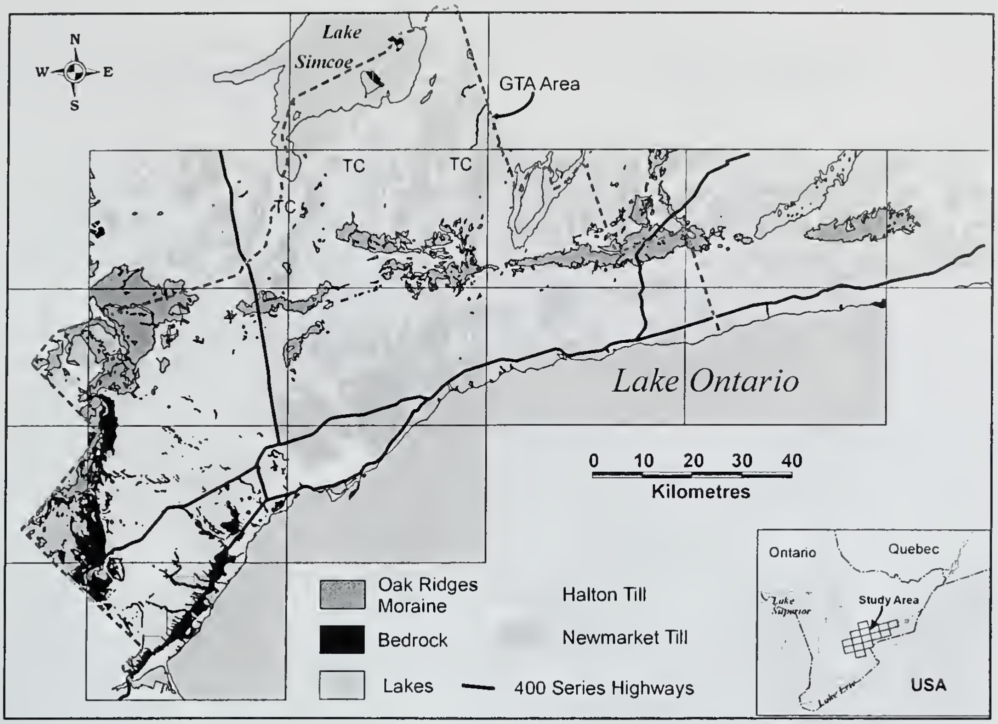

Figure 1. Location of the Oak Ridges Moraine study area in southern Ontario (inset). Generalized geology of the area. Oak Ridges Moraine extends ~160 km from east to west. Note tunnel channels north of the moraine (TC) that show up as white north-south corridors between areas of Newmarket Till.

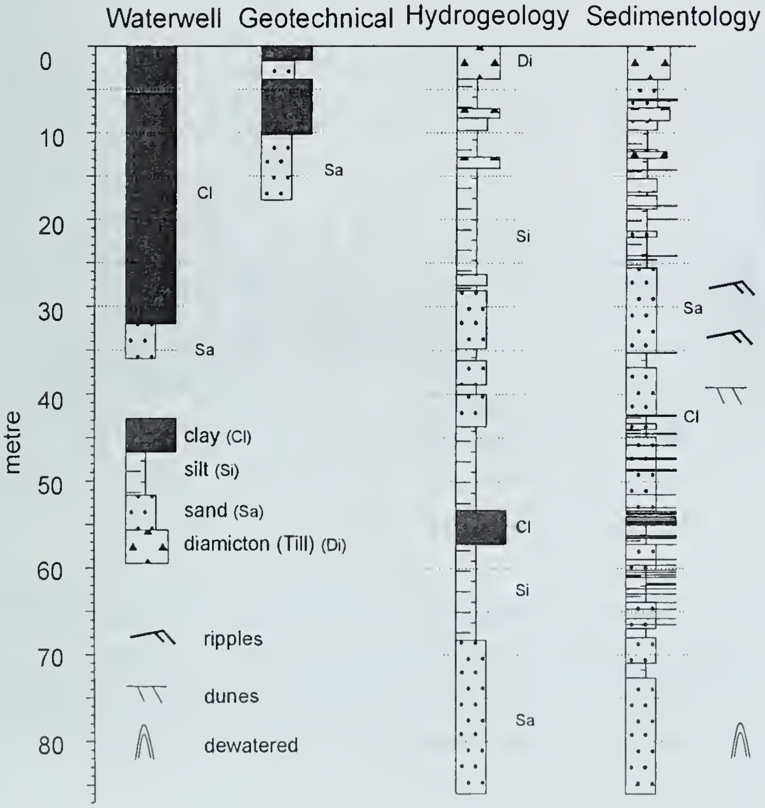

Figure 2. Comparison of archival data and sedimentological data. Note contrast in reported unit thickness, sediment classification, and sediment structures.

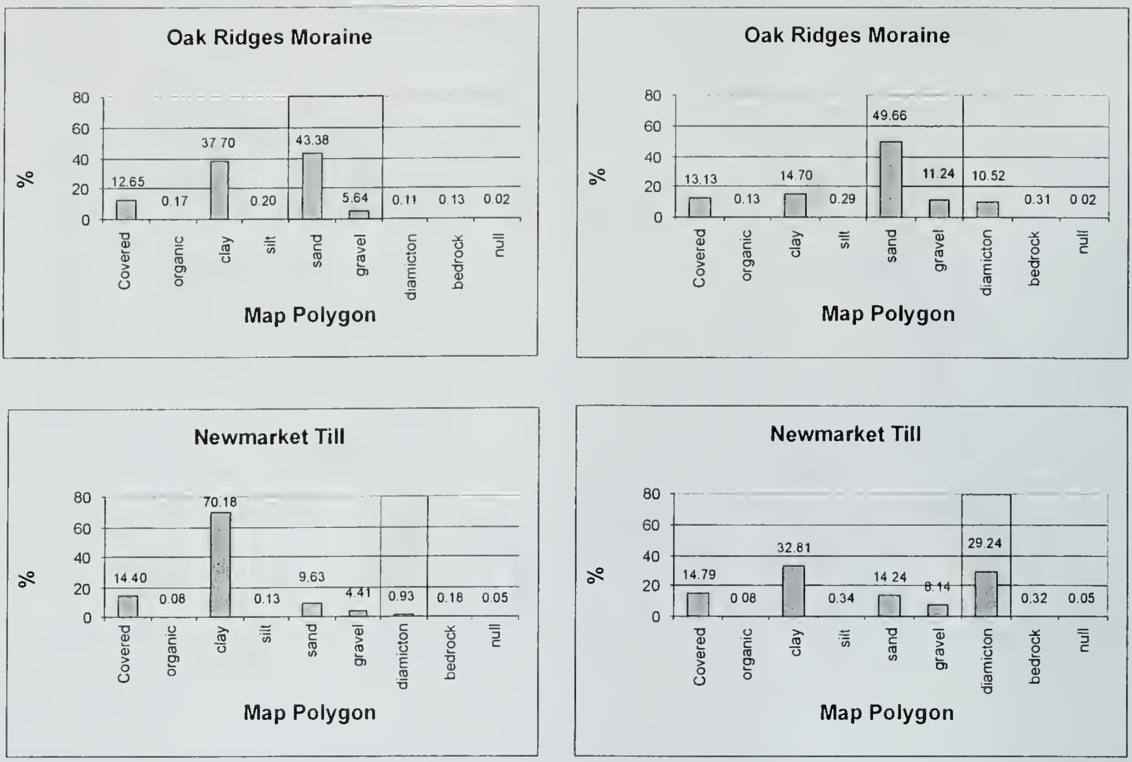

Figure 3. Comparison of two methods of coding archival water well data with the surficial geology, left column is FAM, right column is RBM. Grey band indicates material that best matches the surficial geology unit. Note the high percentage of reported clay. Modified from Russell et al. 1998.

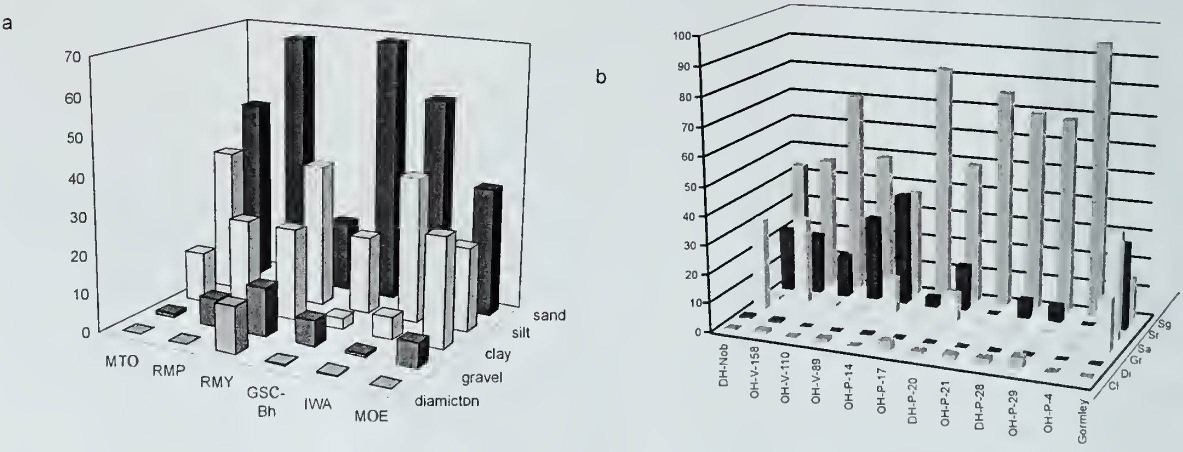

Figure 4. (a) Comparison of composition of Oak Ridges Moraine based on archival data sets and GSC data. (b) Moraine composition using sediment facies coding for continuous core and outcrop sections . MTO - Ministry Transport Ontario (geotechnical); RMP- Regional Municipality of Peel, RMY- Regional Municipality York, IWA - Interim Waste Authority, (hydrogeology); GSC - Geological Survey of Canada (sedimentology); MOE - Ministry of Environment water wells. Sg - graded fine sand - silt, Sr - ripple scale cross-laminated sand, Sa - dune scale cross-stratified sand, Gr - gravel, Di - diamicton, Cl - clay (From Russell, 2001).

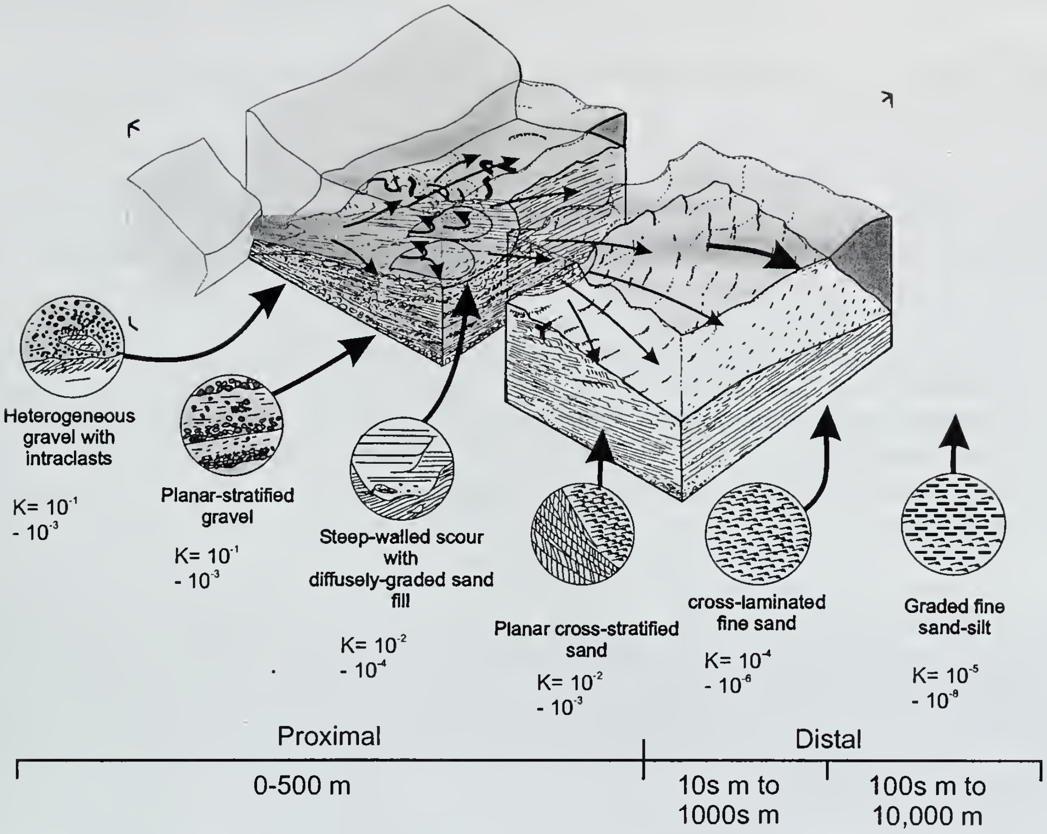

Figure 5. Depositional model of a subaqueous fan element of the Oak Ridges Moraine. Note, rapid streamwise facies changes from gravel to fine sand; inset figures of major sediment facies; K values (m s^{-1}) are general ranges from Freeze and Cherry (1979). Model is modified from Russell, 2001.

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Groundwater modeling: End-user needs from geologic characterization

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Successful site-scale groundwater flow and transport modeling is dependent on the quality and extent of geologic characterization, not only in the immediate area of interest, but also in a regional context. Aspects of geologic characterization important to numerical modeling of groundwater behavior include:

- The three-dimensional geometry of groundwater systems including aquifer and aquitard spatial relationships
- Lithologic variation with estimates of hydrogeologic properties and the spatial distribution of these properties
- Regional geologic controls on groundwater behavior for development of model boundary conditions

Using the results of Argonne National Laboratory's QuickSiteJ expedited site characterization process, three-dimensional, numerical groundwater flow and transport models were developed to evaluate the fate and transport of carbon tetrachloride contamination in the shallow groundwater surrounding a former grain storage facility at Murdock, Nebraska. Integration of quality assured geologic, hydrogeologic, and geochemical data obtained from extensive field sampling through the QuickSiteJ program provided the conceptual basis for the modeling and the parametric constraints on the groundwater model attributes.

The specific purposes of the Murdock groundwater flow and CCl_4 transport modeling effort were to:

- Understand the dynamics of groundwater flow in and around the area of CCl_4 contamination as they are influenced by recharge from precipitation, discharges to local springs and seeps, and natural boundaries to groundwater flow
- Identify preferred pathways of groundwater flow
- Predict long-term migration of dissolved CCl_4 at the Murdock site
- Support development of an efficient, effective, and comprehensive, groundwater level and contaminant monitoring scheme

This poster presents the process of site-specific groundwater modeling in relation to the needs from geologic characterization. The experience from developing three-dimensional, numerical groundwater flow and solute transport models for the Murdock, Nebraska shallow groundwater system is the basis for the demonstration of the importance of detailed geologic characterization in groundwater modeling. The physical aspects of model development are described in association with the necessary geologic input and spatial scale of required data. Both site specific and regional data requirements are discussed.

Regional hydrogeology, models and land use planning, Oak Ridges Moraine, southern Ontario

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Recent development proposals in Ontario have focused attention on the hydrogeology of the Oak Ridges Moraine (ORM), north of Toronto, and in particular, on the use of geological models in guiding hydrogeological understanding. Better understanding of the geological and hydrogeological settings will improve the scientific basis for land use planning decisions and will help reduce conflicts in growth areas (Fig 1a). An important aspect of impact assessment is the accurate identification and assessment of hydrogeological functions such as present or future groundwater supplies or habitats sustained by groundwater discharge. Development investigations traditionally rely on site-specific data and analysis, often at shallow depths for use in site design. However, such investigations can be inadequate to assess hydrogeological functions where groundwater flow systems extend beyond the site boundaries. We endorse the use of regional geological models (Fig. 2) to develop hydrogeological understanding at the scale of the groundwater flow system that enables identification and evaluation of potential impacts at receptors such as streams, lakes, wetlands, and wells. Basin analysis methodology provides geologists with an implicit regional focus, a set of recognized techniques for regional analysis, and thus, a framework for site-specific studies.

Hydrogeological investigations frequently use a "layer cake" stratigraphic model. Although such a model may be valid in places, it may also reflect poor data quality and distribution or inadequate scale of investigation. Several geological settings, particularly in glaciated terrain, cannot be accurately modeled by simple “layer-cake” stratigraphy. Although a site-scale investigation may confirm a layer-cake model locally, such a model may be less applicable at the regional scale. Even a set of deep, cored boreholes can fail to identify large or regional hydrogeological structures as demonstrated in a nearby landfill search investigation (Fig. 3). In such cases, continuous data (e.g. seismic profiles) or a conditioned 3-D, archival dataset at the regional scale can be of assistance (Logan et al., 2000). To guide data collection at the appropriate scale, there is a need to develop one (or more) conceptual models based on a review of geological data. Development of a hydrogeological model generally requires early sensitivity testing, identification of data gaps and collection of suitable new data. New data should allow sufficient characterization of the groundwater flow systems and should be used to test and potentially revise the conceptual model(s).

A terrain model can be used to illustrate the hydrogeological setting of the ORM (Fig. 1b). The model shows permeable moraine uplands overlying a dissected regional aquitard. The geological model identifies 6 major stratigraphic units (Fig. 3). A key element in the model for hydrogeological understanding is breaches within the regional aquitard. Simple hydrogeological scenarios (Fig. 4) illustrate the potential influence on flow that may occur from breaches in a regional aquitard (Martin and Frind, 1998). Where the aquitard is not breached, groundwater flow is expected to occur predominantly within the thick, sandy unconfined ORM aquifer above the aquitard. The pattern of baseflow discharge in adjacent streams suggests that a portion of the recharge may flow vertically through a breach in the aquitard and discharge farther downstream (Dixon Hydrogeology, 1997; Fig. 5). Other sedimentological, stratigraphic and hydraulic data also suggest vertical connections across the regional aquitard (Fig. 6).

In summary, regional continuity in aquitards can rarely be established from site testing alone. Complex stratigraphy with vertical hydraulic connections may alter groundwater flowpaths from what would be expected in simple settings. Such vertical hydraulic connections may affect discharge patterns (Fig. 5) and the location and nature of hydrogeological functions. The integration of a regional geological model into understanding at the flow system and site scales will assist site design, the nature and scale of data collection, data analysis and interpretation, and sensitivity testing.

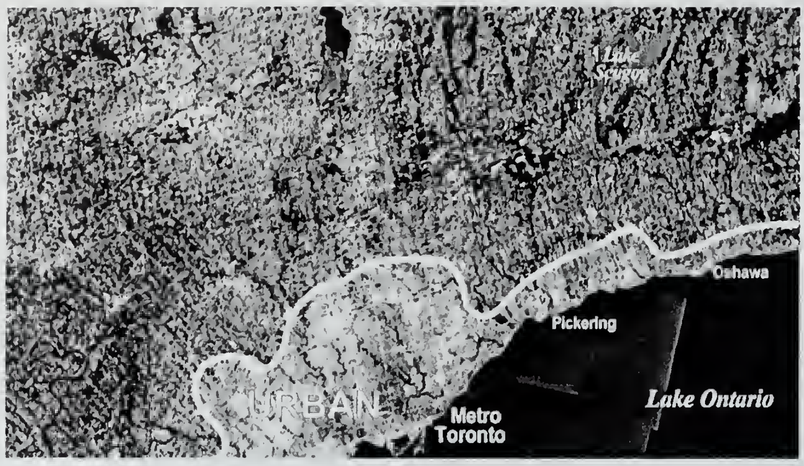

Figure 1. a) Thematic Mapper satellite image shows continued urban growth north of Lake Ontario into agricultural and forested areas.

Figure 1. b) Digital elevation model (DEM) defines a prominent E-W ridge, Oak Ridges Moraine (ORM), which is the drainage divide between lakes Ontario and Simcoe (north of Holland Marsh). Do large features like the Holland Marsh, and its buried southward extension beneath the ORM, have a potential influence on regional groundwater flow?

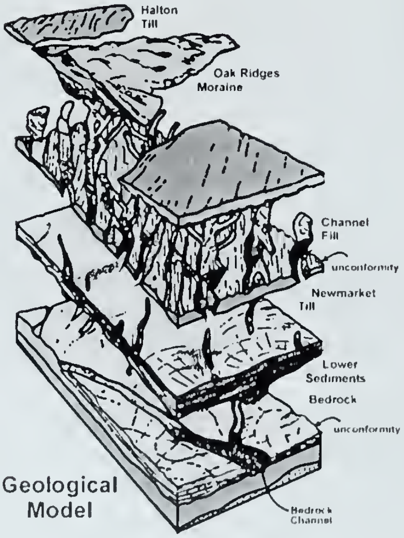

Figure 2. Geological model of the ORM area consists of 6 main hydrostratigraphic units (bold) with erosional unconformities. This complex architecture may allow for enhanced hydraulic connection between ORM deposits and Lower Sediments via the ORM-channel aquifer system.

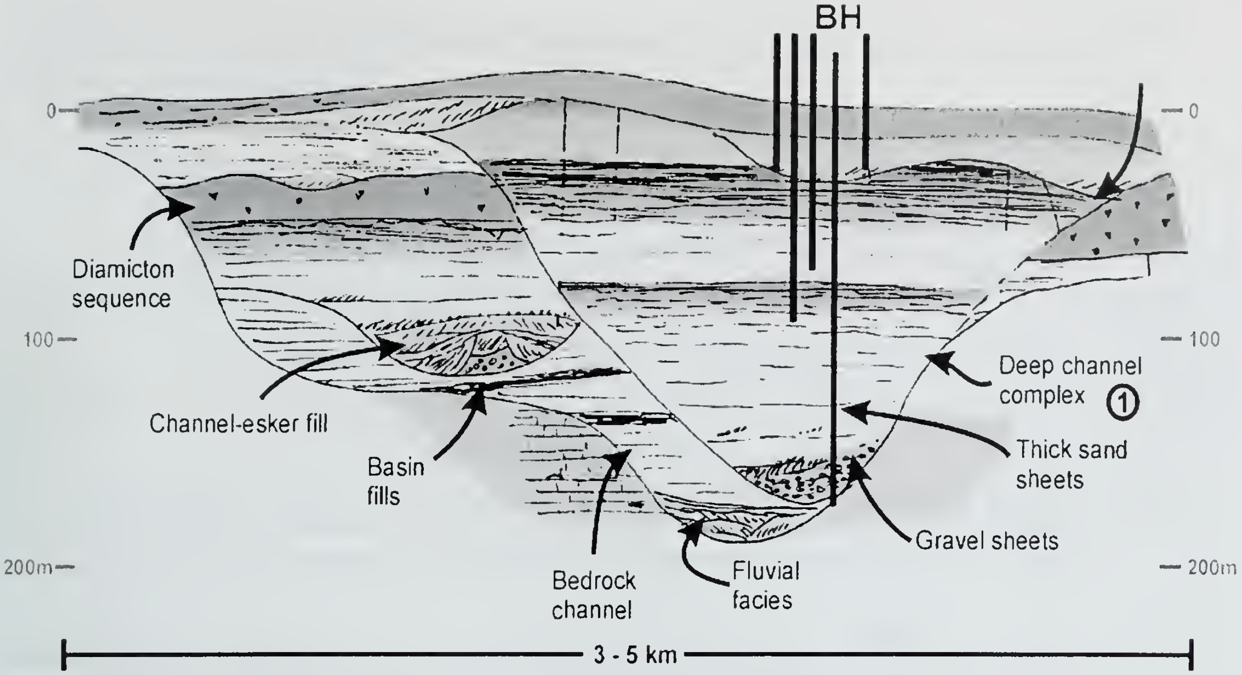

Figure 3. A schematic section of a deep regional channel (1) that extends for many kilometers beyond the cluster of boreholes drilled at site BH. This site-drilling plan may not recognize the deep channel without a conceptual model anticipating its presence at this scale, or, in the absence of continuous data such as seismic profiling.

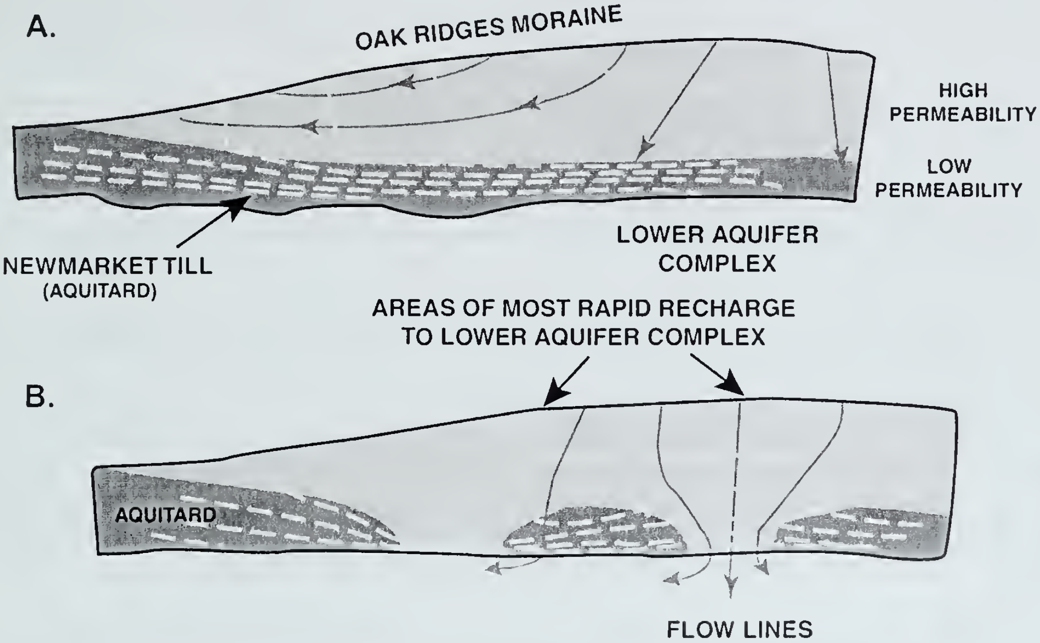

Figure 4. Flow pattern scenarios illustrating the potential effects of aquitard breaches on groundwater flowpaths (Dyke, 1994).

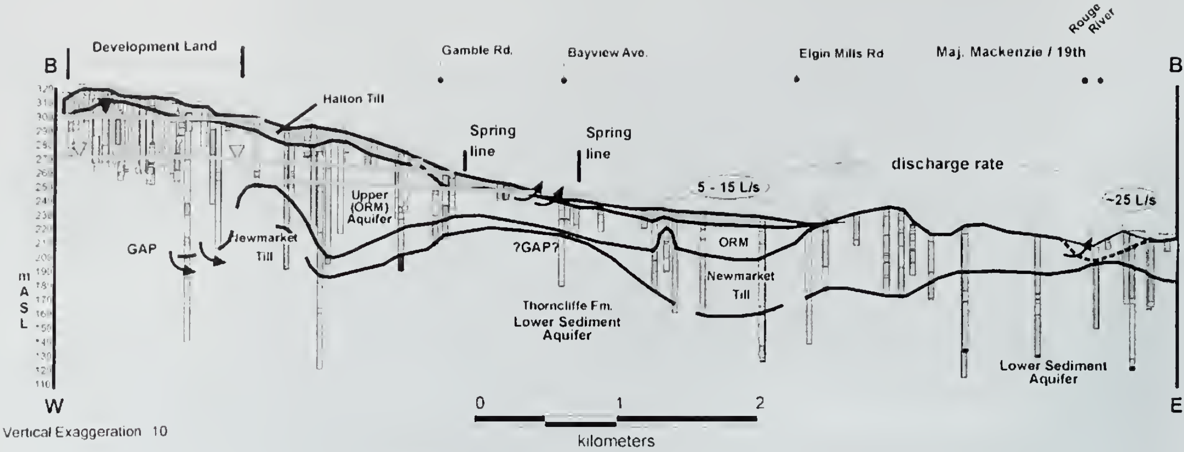

Figure 5. Detailed geological cross-section along the flow system with stream baseflow estimates along a headwater tributary. Geology and distribution of discharge are consistent with aquitard gaps (Fig. 4b) leading to enhanced vertical flow in recharge areas and discharge farther down gradient in the watershed.

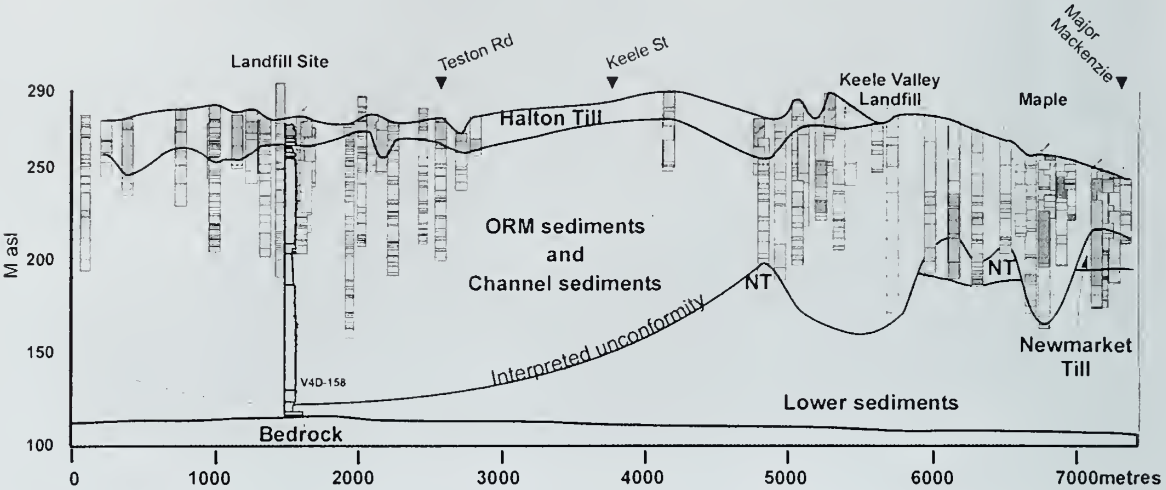

Figure 6. Cross-section derived from seismic profiles and cored boreholes shows 3-5 km wide sandy to silty channel sediments at Maple. Such cross-sections provide the regional context for interpreting vertical hydraulic connection at nearby development sites.

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A method for three-dimensional mapping, merging geologic interpretation, and GIS computation

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A cooperative geologic mapping project was conducted by the Illinois State Geological Survey (ISGS) and the United States Geological Survey (USGS) to map the Quaternary deposits in east-central Illinois (figure 1). This area provides an excellent geologic setting to develop and test new techniques for mapping Quaternary deposits in three dimensions (i.e., mapping the thickness and distribution of geologic materials both at land surface and in the subsurface), because it has diverse Quaternary geology and thick, regional sand and gravel aquifers within a buried bedrock valley system (the Mahomet Bedrock Valley). The Mahomet Sand, which fills the deepest portions of the bedrock valley, is the thickest and most widespread glacial aquifer in the system. In addition, overlying the Mahomet Sand (Mahomet Aquifer) are sand and gravel units intercalated with fine-grained deposits. Where the Mahomet Sand is absent, these aquifers are important sources of water for rural farmsteads, communities, and industries.

The Quaternary deposits of east-central Illinois are the product of multiple glaciations and three distinct bundles of Quaternary sediments are prevalent - those from the Wisconsin, Illinois, and pre-Illinois Episodes, all containing fine-grained diamicton and sand and gravel deposited by glacial ice. Because these sediments are relatively thin and, in places, discontinuous, they are a distinct challenge to map, especially in the subsurface. Traditionally, a map of the elevation of a subsurface unit has been drawn by the geologist, based on (usually sparse) outcrop and well data and a general model or understanding of how the unit came to be deposited and subsequently altered by erosion.

From the rapidly-growing field of Geographic Information System (GIS) science and software, automated methods have emerged for creating maps once produced only by the geologist's hand. These computer-generated maps, however, have serious deficiencies especially in areas where data are sparse and/or of uneven quality. This presentation describes a method that combines the geologist's knowledge of regional geology with the computational power of a GIS to create maps superior to those produced by either approach used alone.

Goal and products

The primary goal of our study was to build upon prior regional geologic investigations, using newly-refined stratigraphic data to produce updated, revised maps that could be used for various computer-aided applications such as groundwater modeling. Our second goal was to produce these maps using digital methods because county health and planning departments, state environmental, agricultural, and health agencies, water resource utilities, and other entities increasingly are using GIS to support decision making and planning.

Because computer-based mapping of deposits in three dimensions is not yet a common, well-established practice, we developed GIS-based methods to integrate point (key stratigraphic control data) and areal (geologic mapping) data. These methods are briefly described in Soller and others (1998 and 1999). With these methods, a set of geologic maps was produced that show the three-dimensional nature of the region's Quaternary deposits and uppermost bedrock (Soller and others, 1999).

To help realize the second goal, we worked with local community and industry representatives to identify how 3-D geologic map information could help them model and manage the region's groundwater resources. Partly as a result of those meetings, the Mahomet Aquifer Consortium was formed. As noted at their Web site (http://www.MahometAquiferConsortium.org/), the Consortium's goal is "to further study the Mahomet aquifer on a regional basis and to develop a plan for the management of this valuable resource."

Developing the stratigraphic database and maps

The three-dimensional distribution of geological units can not be properly mapped and understood without spending enough time and money to obtain the required high-quality stratigraphic information from boreholes and geophysical surveys. This is especially true for glacial deposits, as they commonly are thin (generally <200') or patchy in distribution, and often have abrupt facies changes across short distances.

Over many years, the extensive ISGS collection of records from wells and borings has been used to interpret age relationships and lithology for geologic mapping and groundwater studies in cooperation with local, State, and Federal partners. A cornerstone in building our database was identifying a set of "key stratigraphic control points" (Kempton, 1990) from the ISGS collection of subsurface data. Key stratigraphic control points have high-quality data where samples have been described and/or well logs interpreted by geologists or engineers, and the locations of the data points are verified. From these control points, we built a stratigraphic database comprised of 177 such borehole records (about 1.5 per township, see figure 2). Included in these data were borehole logs and samples from six borings, to an average depth of 280 feet, done specifically for this study. Boring locations were in the presumed thalweg (deepest part) of the bedrock valley and in areas where data were sparse. Other key control points consisted of water wells with boring logs and sample sets of geologic materials (collected when the well was drilled). Representative well cuttings were described and samples assigned into various lithostratigraphic units.

Key stratigraphic control points served as principal data for constructing maps of each stratigraphic unit. These data were supplemented by more than 2000 secondary control points, mostly water-well drilling records having more generalized driller's descriptions of the geologic materials. Water-well data provided additional mapping control, especially for units showing a strong lithologic contrast with adjacent units (for example, the bedrock surface, or the top of the Mahomet Sand).

From these data and an understanding of the geologic processes that prevailed in the region, a set of maps was produced, one for each stratigraphic unit. When the map of each geologic unit had been compared with those stratigraphically above and below, and all maps were found to nest properly, they were processed with EarthVision software, which is a high-quality software tool for geologic modeling. [For our purposes, it was preferable to generate each geologic map in ArcInfo software, and to import the file to EarthVision simply to create a three-dimensional visualization.] Apparent inconsistencies or errors in stratigraphic unit geometry were evaluated and, if necessary, the maps were revised in ArcInfo before completing the final set of 2-D and 3-D maps and images. In this way, the goal of producing an internally-consistent set of maps was realized. Finally, maps of unit thickness were computed in ArcInfo by calculating the difference in elevation between the top of the unit and the top of the underlying unit. In EarthVision, various 3-D perspective views, cross sections, fence diagrams, and vertical and horizontal slices through the deposits were generated for visual analysis (for example, see figure 3 and map images and animations at <http://pubs.usgs.gov/i-maps/i-2669/>).

Summary

An internally-consistent, three-dimensional geologic model was developed for a portion of east-central Illinois, including the Mahomet Bedrock Valley and surrounding uplands. Based on our experience, and the time needed to generate this model and set of maps, we advise that the planned and potential uses of the map products be carefully evaluated before a mapping project is begun. Providing an internally-consistent, three-dimensional model is essential if an analytical use is planned, such as development of a ground-water flow model. However, if adequate high-quality data are not available, or a raster-based analytical purpose not foreseen, these maps need not be developed. Instead, more conventional, vector-based methods for preparing maps of each surface may be used to provide a general, visual depiction of the geologic framework.

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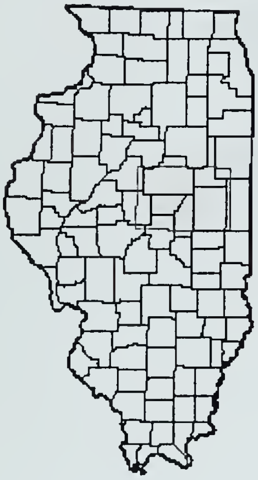

Figure 1. Location of the map area, east-central Illinois

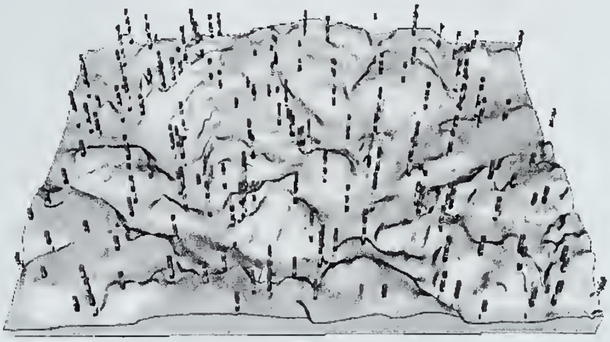

Figure 2. Perspective view of the map area showing the distribution of 177 key stratigraphic control points relative to the bedrock topographic surface. Viewpoint is from the south. Vertical exaggeration is approximately 30x.

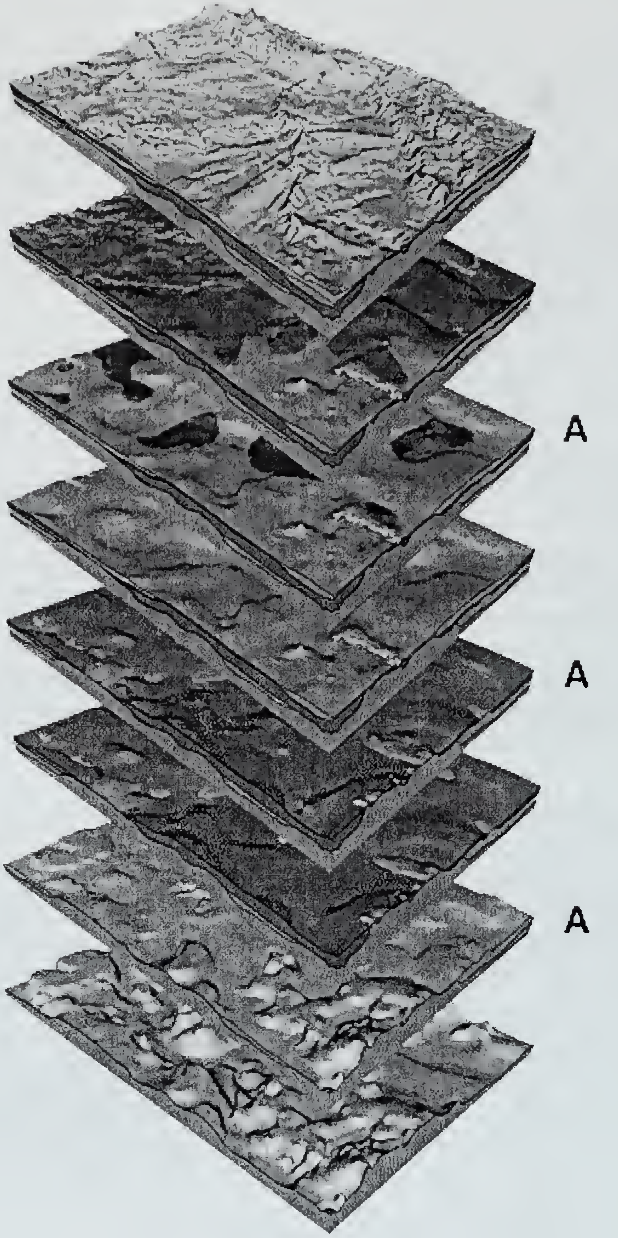

Figure 3. 3-D geologic maps showing the various geologic layers. The mostly discontinuous groundwater aquifers are shown in the images marked as "A". The lowermost of these is the Mahomet Sand, an important regional groundwater resource. Viewpoint is from the southeast. Vertical exaggeration is approximately 30x.

Three-dimensional models of shallow aquifer systems derived from interpolation of lithologic descriptions in water well logs; Lake Rim area, northwest Indiana

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We have been exploring the use of lithology data extracted from water well logs to develop three-dimensional models of aquifer systems in the glacial and lacustrine depositional environments of northwestern Indiana. Our methodology involves classifying all lithologic units within a sample log on the basis of their (inferred) equivalent hydraulic conductivity. We recognize six categories (labeled 1 through 6) with each category value representing the negative log of its equivalent hydraulic conductivity. Initial analyses using ordinary kriging to interpolate the distribution of material types indicated that kriging facilitates identification of the main aquifer(s) in an area of study (i.e., their basic extent and connectivity). However, a statistical comparison between the frequency distributions of material types in the well logs and the distribution derived from the results of the kriging revealed a discrepancy. The kriged data exhibited a unimodal distribution with the highest frequency associated with intermediate material types (equivalent conductivity category 4). In contrast, the well log data has a bimodal distribution with the intermediate material types having a relatively low frequency of occurrence. A post-processing algorithm has been developed that screens all intermediate material types in the kriged data set. If the intermediate value occurs outside of a specified search radius (250 meters), its value was altered by adding or subtracting one standard deviation of apparent hydraulic conductivity based on the empirical frequency distribution. Distributions altered in this way matched those of the well log data more closely.

Construction of a geological model of the Winnipeg region for groundwater modeling

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Nearly all of the one million inhabitants of the Province of Manitoba, Canada, live in the 400-km x 700 - km area of Phanerozoic terrane in the southern portion of the province, adjacent to North Dakota and Minnesota. The majority live in the Winnipeg area, a 200 km x 230 km area in the southeastern corner of the province. The City of Winnipeg obtains water from Shoal Lake, but the 200,000 residents of surrounding areas rely on groundwater obtained from bedrock aquifers. Fresh water in these aquifers consists of modern recharge and relict subglacial recharge, but a saline water system recharged in South Dakota and Montana discharges to the western Red River valley. Research on the long-term sustainability of the fresh groundwater resource is addressing protection of recharge, and ensuring that excessive pumping does not lead to unacceptable lateral migration of the saline waters. Modeling is a key element of this strategy, and a geological model was required. The model was built as follows:

Topography: Having found readily available models to be inadequate, a new model was constructed by the authors, largely from Provincial legal survey data. The resulting model has a grid resolution of 100 m, absolute vertical accuracy of about +/- 3 m, and relative accuracy in tenths of a metre. The data have been used to position drill holes vertically, the geological model hangs from the topography, and the model has provided insight into previously unrecognized geological features.

Bathymetry: Large lakes occur in the area, including Lake Winnipeg, which is 25% larger than Lake Ontario. These are key features in the hydrogeological landscape, and lake-bottom features provide insights into geology. Soundings from 22 hydrographic charts therefore were digitized and a database containing 31,607 digitized bathymetry points was created. These were modeled with shoreline data and locations of shoals, at a grid resolution of 100 m.

Surficial geology: Subsurface modeling was guided by the most detailed available surficial geological mapping. At this stage, the subsurface model is not linked to the polygons, due to the much greater detail of the surficial geological mapping, relative to the resolution that could be achieved in the subsurface.

Quaternary stratigraphy: Key inputs to the 3D model of the sediments were cored holes logged by geologists, and geophysical surveys. These high-quality results were extrapolated laterally using water well data from 80,000 sites (Figure 1). Much effort was required to parse the 75,000 unique lithological descriptions in this database, and the results were interpreted using a scatterplot approach (Figure 2). The 200 km x 230 km Winnipeg area was divided into 46 strips each 5 km wide, and a large colour chart was printed for each strip, showing all drillhole data, surficial geology, and surface elevation. The drillhole data, colour-coded for lithology, were interpreted as a series of vertical maps (Figure 3), using the same methods used to compile plan-view maps. The interpretation was captured at 5 km spacing, and gridded.

Bedrock geology: A new set of 1:1 million bedrock polygons for the Phanerozoic units was constructed, linking outcrop to subcrop, to produce stacked polygons.

Phanerozoic stratigraphy: Structure contours for each Phanerozoic unit were gridded.

Figure 1. Location of water well data in southern Manitoba.

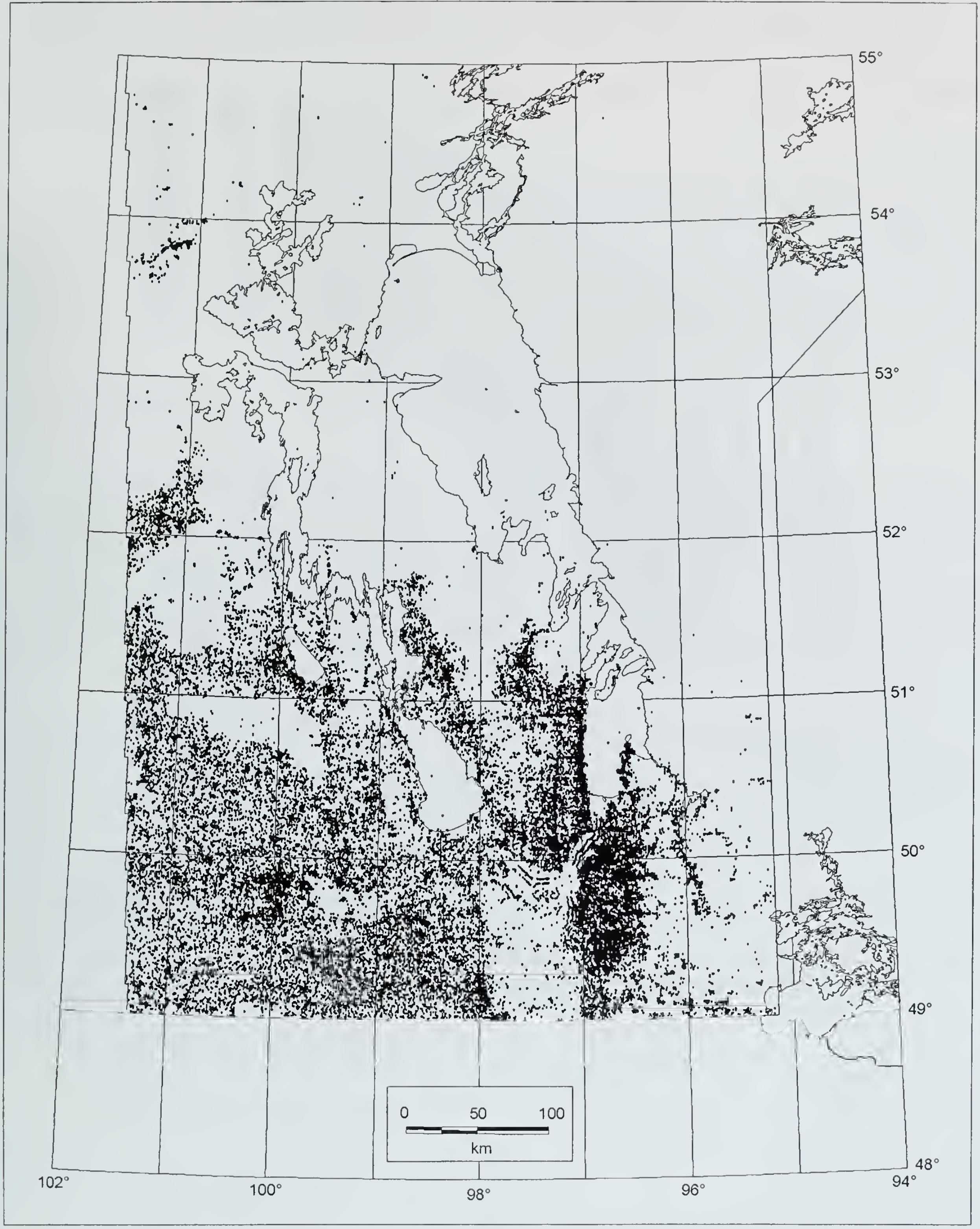


Figure 2. A portion of the drillhole data scatterplot for the 5 km swath shown in Figure 3; vertical scale in m asl, horizontal scale 75 km.

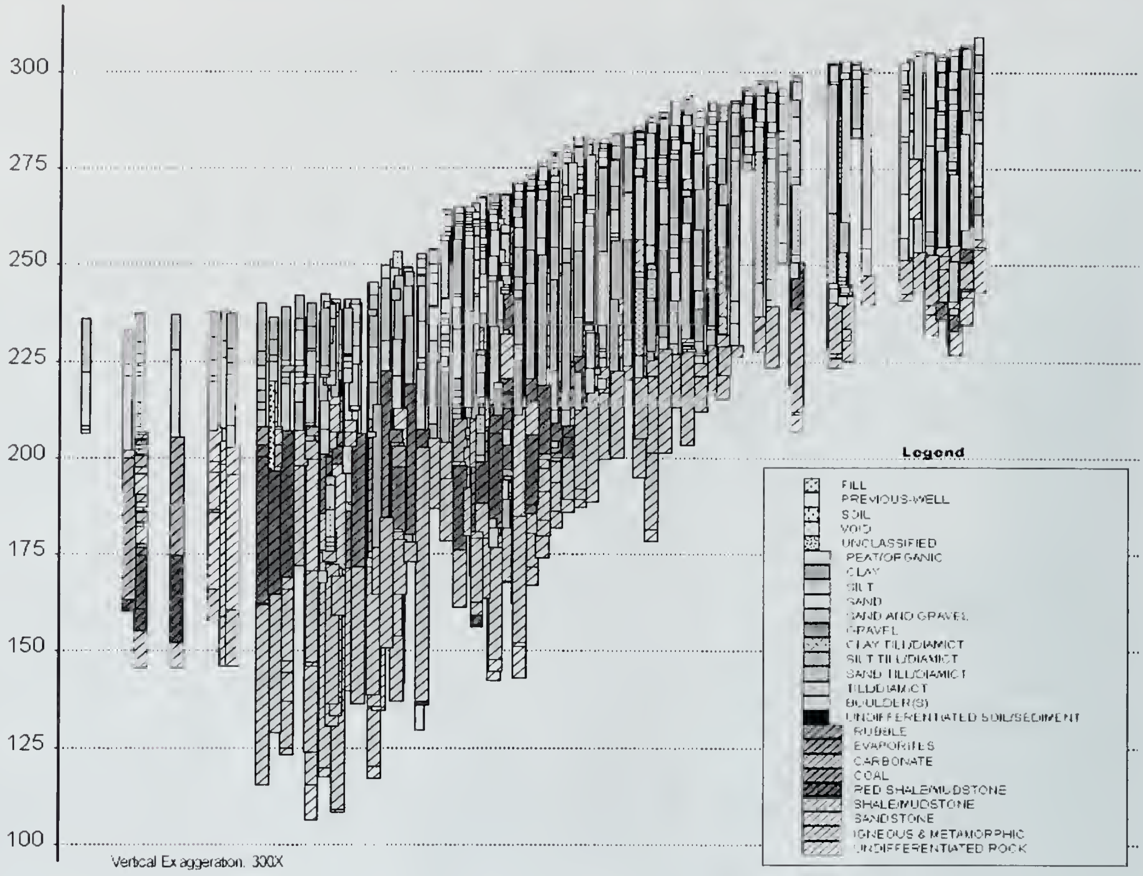
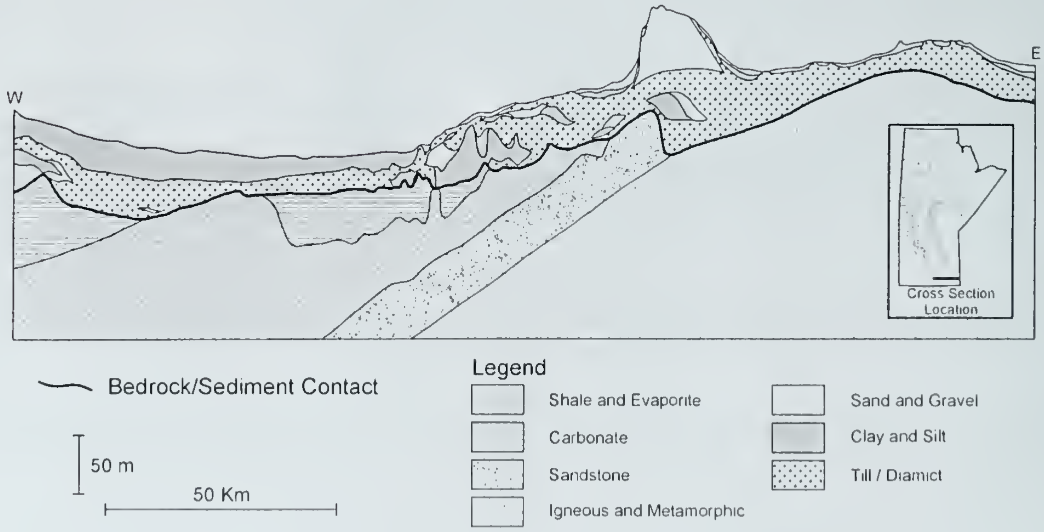


Figure 3. One of the 46 interpreted sections for the Winnipeg area.



Mapping buried glacial deposits in Washington County, Minnesota-Applications to hydrogeologic characterization of glacial terrains.

Tipping, Robert G., and Gary N. Meyer, Minnesota Geological Survey, University of Minnesota, 2642 University Avenue, St. Paul, MN 55114

The Minnesota Geological Survey, in cooperation with the Washington County Department of Environment, Health and Land Management, recently completed mapping buried and surficial glacial deposits within a moraine complex in Washington County, Minnesota (Fig. 1). The project involved delineation of till boundaries within the sub-surface followed by the creation of digital elevation models (DEMs) from the contoured surfaces. The intervals between till layers were mapped as sand and gravel. In addition, the ability of these units to transmit water was estimated using available till permeability data from the study area. The result is a three-dimensional picture of the distribution and water-bearing character of the unconsolidated material above the bedrock surface. This presentation outlines methods used to construct the digital elevation models of the till surfaces, and how those methods are being applied elsewhere in the state.

Data used to construct the till DEMs came primarily from water well drill logs contained in the state water well database, the County Well Index (Fig. 2). Because of distinct color differences between tills in this area, contacts are commonly described in the drill logs. These contacts were identified and coded for wells whose location and elevation could be verified, thereby permitting the contact elevations to be contoured. Because of the complexity of glacial deposits within the study area, contours of contact elevations were done by hand, rather than using interpolation algorithms. 7,415 well records were used for this study. Till contacts were identified in 2,146 wells. Interpretation of water wells was supplemented with three Rotosonic core holes distributed over the study area (Fig. 2).

The resulting DEMs have a number of applications. Till unit thicknesses can be calculated by subtracting the bottom elevation from the top elevation (Fig. 3). In addition, the DEMs can be used to produce cross sections for any site in the county (Fig. 4). By showing the distribution, thickness and permeability of the subsurface till units in grid form, the DEMs are suited for incorporation into a grid based groundwater-flow model such as MODFLOW. The DEMs, till permeability estimates, and derivative maps are currently being applied to several different water quality issues: 1) to help estimate rates of storm-water recharge in southwestern Washington County; 2) to model recharge in an area that has historically high water table elevations in north-central Washington County–presumably due to low infiltration rates; and 3) to understand variations in stream flow along one of the few remaining designated trout streams in the metropolitan area. Elsewhere in the state, methods from this study have been used to calculate the distribution and thickness of a regional surficial sand aquifer along the Mississippi River corridor from Brainerd, Minnesota to the Twin Cities metropolitan area, for use in a USGS regional groundwater-flow model.

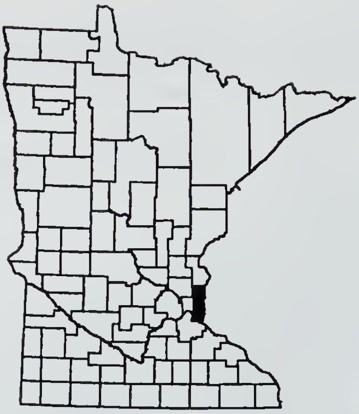


Figure 1. Location of Washington County, Minnesota

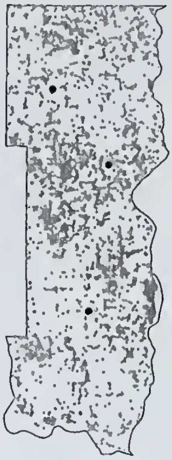


Figure 2. Locations of data points used in this study: 7,415 water wells shown in gray; 3 Rotosonic holes shown in black.

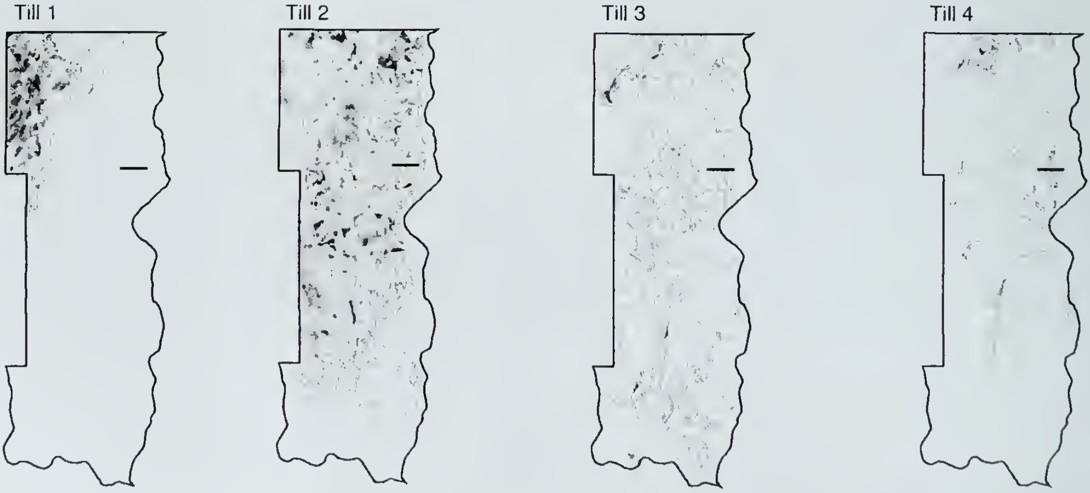


Figure 3. Gray-scale images showing distribution and thickness of 4 tills. Thickness calculated from till top and bottom DEMs. Till thickness ranges from a few feet (lighter shades) to 210 feet (darker shades). The short dash in the northeast-central section of the county is the location of the cross section in Figure 4.

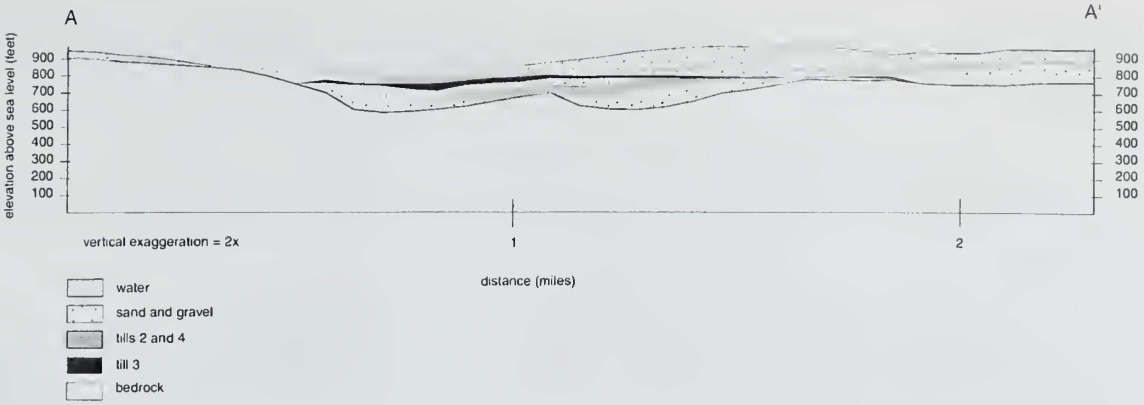


Figure 4. Cross section constructed from land surface, till, and bedrock DEMs, showing tills 2, 3 and 4 and the distribution of sand and gravel. Location of cross section shown in Figure 3 (till 1 not present at this location).

The Seattle-area geologic mapping project and the geologic framework of Seattle

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Introduction

The Puget Lowland is in a unique geologic setting: near a subducting tectonic plate and having been glaciated over 6 times in the last 2 million years. Because of this setting, the Puget Lowland is subject to abundant geologic hazards, such as volcanic activity, earthquakes, faulting, landslides, liquefaction, and other ground failures. Because of the cost of damage that can result from geologic hazards, the City of Seattle and many other agencies want to mitigate for geologic hazards. Recent events have demonstrated the need for such concern. The M-6.8 Nisqually earthquake occurred on Feb 28, 2001 with an epicenter about 50 kilometers from Seattle, and caused damage to buildings, bridges and lifelines. Earthquake-induced ground failures correlated to local soil conditions and included landslides, loss of bearing strength, and lateral spreading. The estimated cost of damage exceeded 2 billion dollars.

Enormous research efforts -- involving scientists from the University of Washington (UW), other universities, U.S. Geological Survey USGS, City of Seattle, WA DNR, local agencies, and private businesses -- are focused on identifying geologic hazards in Puget Sound. These efforts include: geologic mapping, geophysics to identify bedrock structure, upgrade of our seismic network, paleoseismology, identifying properties of geologic materials, age determinations, landslide mapping and modeling, high-resolution bathymetry, and volcanic hazard assessment.

The Seattle-Area Geologic Mapping Project

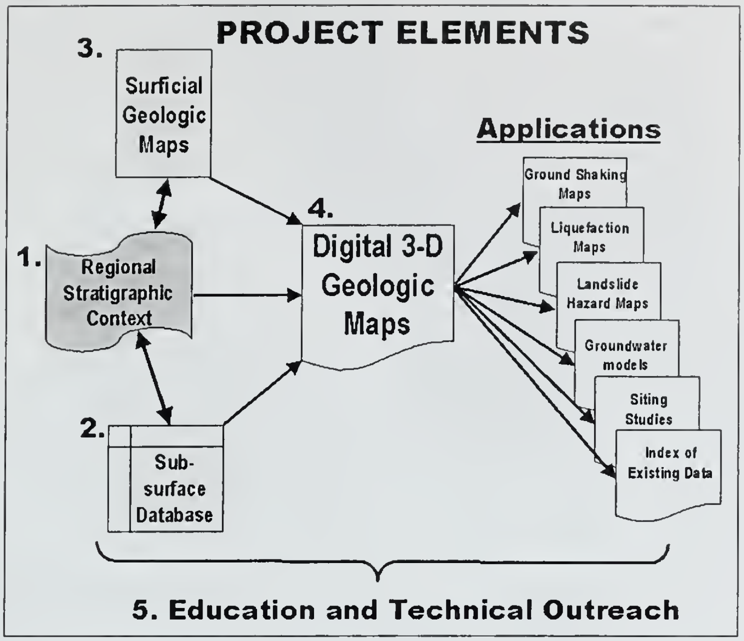
A collaborative research project was started in 1999 at the UW with the USGS and the City of Seattle. The goal of the Seattle-Area Geologic Mapping Project is to develop a comprehensive geologic database and set of geologic maps to support hazard assessments and land use decisions.

The only available geologic mapping of the City itself is over four decades old. None of the active faults in the region, one of which is now known to pass directly under the City and to have produced violent shaking and ground rupture about 1100 years ago, are even recognized on the existing map. This project will rectify this shortcoming by developing a detailed understanding and representation of the three-dimensional distribution of geologic materials beneath Seattle and to embed that information in the context of a coherent, regionally integrated geologic framework for the south-central Puget Sound region. The new maps are just the beginning. All of the research efforts focused on hazards have and will continue to result in new findings on the geology and tectonic setting of the Lowland.

The project has five components, each designed to address specific objectives:

1. **<u>Regional Stratigraphy/Chronology/Training</u>**

- Determine age and identification of Quaternary units to help unravel the deformation history.
- Provide detailed descriptions of the Quaternary units and their properties (strength, thickness, lithology, source [volcanic mudflow], etc.) for use by planners, engineers, and consultants.
- Standardize nomenclature for all the geologists working in the Puget Lowland and train other geologists, unfamiliar with Puget Lowland geology.



2. **Surficial Geologic Maps Across the Central Puget Lowland**

- New geologic map coverage at 1:12,000 scale, in four quads, for the City of Seattle. The maps are being produced (digitally and hard copy) on shaded DEM bases showing all data points (outcrops and borings).
- Continued production of new geologic maps at 1:24,000 scale from the south-central Puget Lowland

3. **Subsurface Database for the City of Seattle**

- GIS-based compilation of existing geotechnical data and new outcrop data, ultimately maintained by the City and available to the public in perpetuity.

4. **Three-Dimensional Geologic Model of the City of Seattle**

- Geologic interpretation of the subsurface database, integrated with other project components into a graphically supported geologic database and map display, supported by and available from the City of Seattle in collaboration with the University and the USGS.

5. **Education/Technical Outreach**

- A Technical Advisory Group, assembled to ensure that the database suits current and future needs, has been formed to support these tasks. Its membership emphasizes senior members of the region's geologic and geotechnical community, both private and public.
- Lead, convene, and participate in seminars, conferences, workshops to educate the scientific and nontechnical community about the baseline geologic setting
- Prepare a book, for the public, on the Geology of Seattle.

Database

For the Seattle Geologic Mapping Project, we have developed, and are now populating, a relational database of existing subsurface geologic data that covers the City of Seattle. This database accommodates both spatial and nonspatial data by following a GIS-based approach. The database is designed to accept new data types as they become available, and serves as a template as our project expands its geographic coverage. The database includes fields for the "raw" data as well as fields for geologic interpretations and for the "metadata" that carries information on original source documents, original scale, and anticipated data quality. We have adopted a basic three-level structure for the core of the database, and a simplified listing of the main tables is shown below. We have been working in MS ACCESS but are planning to change to ArcSDE with an Oracle database backend.

Document Data
- Document Area
- Document Type
- Document Source
- Document Author
- Document Name
- Project Type
- Project Address

⇨

Point Data
- Point Location
- Point Name
- Point Type
- Location Confidence
- Point Depth
- Point Elevation
- Point Author
- Point Date
- Number of Wells

⇨

Layer Data
- Layer Type
- Layer Depth
- Layer Description
- Density/Consistency
- Major/Minor Material Types
- Debris/Organics?
- Interpreted Geologic Unit
- Interpreted Geologic Features

Mapping Examples

Comparison of the existing geologic map for the City of Seattle (Fig. 1) with the new mapping of the Seattle Geologic Mapping Project (Fig. 2) shows the improvements in mapping. The area displayed covers the Mee Kwa Mooks area of West Seattle. Improvements include: (1) greatly increased range and quantity of data sources, particularly geotechnical explorations and new field exposures; (2) recognition of greatly expanded landslide areas (outlined dots) that correspond well to areas of historic landsliding (triangles), note the newly identified older landslide area at the edge of the upland; (3) more precise delineation of geologic unit boundaries and recognition of folding of 20,000-year-old beds; (4) inclusion of previously unrecognized geologic units ("Qob" on the lower map); (5) more precise and intuitive rendering of topography; and (6) full digital record of all data sources, mapped contacts, and geologic interpretations.

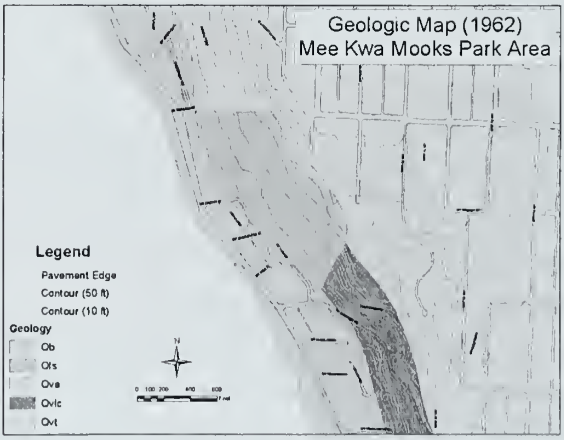


Figure 1. Existing geologic map for the City of Seattle

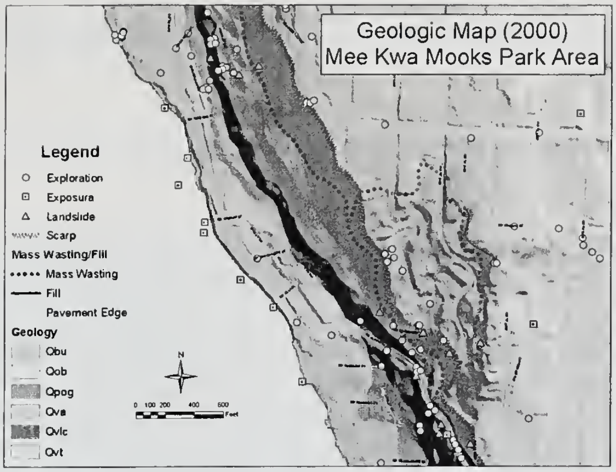


Figure 2. New mapping from the Seattle Geologic Mapping Project

Geologic Framework of Seattle

The near-surface geology of the Puget Lowland strongly influences the pattern of ground motion during earthquakes, groundwater flow paths, slope stability, and bearing strengths. The Lowland is underlain by Eocene to Miocene volcanic and sedimentary rocks deposited as forearc basin fill over older basement rocks. The forearc basin has undergone north-south shortening, resulting in the formation of several large bedrock uplifts and basins, along with smaller folds and faults. A complex, alternating, and incomplete sequence of glacial and nonglacial deposits rests upon this irregular bedrock topography. The depth to bedrock varies from zero to more than 1000 m below the ground surface. Bedrock outcrops in an east-west band across the Lowland at the latitude of south Seattle and also in the foothills and mountains that form the perimeter of the Lowland. Numerous faults and folds, many of Holocene age, have deformed both the bedrock and overlying Quaternary sediments.

The current landscape is largely a result of repeated cycles of glacial scouring and deposition, and recent processes such as landsliding and river action. The north-south ridges and troughs of the Lowland are the result of glacial scouring and subglacial stream erosion. The ridges are generally composed of Pleistocene glacial and interglacial deposits, which are dense and stiff from overriding by multiple advances of 1000-m-thick ice sheets; intervening troughs commonly contain normally consolidated river and lake deposits of the last ice-sheet advance and post-glacial time. Alluvial sediment, predominantly sand and silt, lies many 10's of meters thick in the major river valleys. The steep bluffs and hillsides that border the river valleys, streams, Lake Washington, and the coastline of Puget Sound are mantled with colluvium, which tends to slide during or following periods of heavy precipitation.

Holocene deltas have extended from the mouths of all of the major river valleys into Puget Sound. The most voluminous of the south and central Lowland, those of the Duwamish, Puyallup, and Nisqually rivers, have been fed by sediment from Mt. Rainier. Subsequent commercial and industrial use in both Seattle and Tacoma has required extensive modification of these deltas, principally in the form of fills and retaining structures, that has resulted in extensive port and transportation facilities on loose, saturated soil deposits.

The use of geologic models for groundwater modeling in radioactive waste disposal programs

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In most countries, the permitting process for radioactive waste disposal generally requires performance assessment (PA) studies that attempt to predict the radioactivity dose to future generations. For geologic disposal programs, PA studies expend great effort on subsurface site characterization and incorporating the resulting conceptual models and data into groundwater models. There are good examples of directly using the geologic model in constructing the groundwater models, such as the inclusion of known structures and hydrostratigraphic units. The geologic model also is used indirectly to infer hydraulic properties and their spatial distributions, to confirm flow patterns, and to suggest processes that may affect the repository in the future. Uncertainties in the geologic model are handled both formally by stochastic simulation and informally by alternative modeling scenarios. The PA studies of several countries illustrate that the available computational resources, model code quality control, and organizational constraints commonly limit use of geologic models within PA groundwater studies.